Sustainable Cities and Society 72 (2021) 103042

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Influence of the Representative Concentration Pathways (RCP) scenarios on the bioclimatic design strategies of the built environment

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ARTICLE INFO

Keywords:
Bioclimatic design
Thermal comfort
Climate change
Built environment

ABSTRACT

Over time, whether through traditional knowledge or the constructive implementation, the relationship of the built environment with the climate conditions of a certain place has been developed. The control of these symbiotic solutions based on the climate-conscious design and their strategic approach have been improved to keep better welfare levels. Due to climate change, however, design strategies could be modified in a context of global warming. This research considers the Representative Concentration Pathways (RCP 2.6, 4.5 and RCP 8.5) to analyse the effectiveness of the design strategies throughout the 21 st century. A total of 6 countries (France, Portugal, Spain, Argentina, Brazil, and Chile) were selected to assess both thermal comfort levels and the need for using HVAC systems in each climate zone and in all future scenarios, so 1,450 cases were studied. The results showed that the less conservative climate change scenarios will affect thermal comfort, thus significantly reducing comfort hours in warm climates. In addition, passive design strategies could be less effective in the future, predominating the use of cooling systems. As a result of this research, future design strategies should be dynamic and permeable for possible scenarios.

1. Introduction

The oil crisis of the 1970s made people aware of climate change effects. Over the years new generations have considered climate change as a major challenge for society, particularly in the 21 st century. Earth's ecosystem is strongly changing: the extinction of species, desertification, sea level rise, and more and more extreme thermal conditions (World Wildlife Fund, 2014). Moreover, the Covid-19 pandemic has shown the effects of future pandemics emerging from the new climate change scenario (Manzanedo & Manning, 2020).

The high energy consumption from anthropogenic activities is among the main generators of climate change. These activities include the building sector; in quantified data, it is responsible for both 40 % of energy consumption (European Commission, 2006; European Environment Agency, 2018) and 36 % of greenhouse gas emissions (European Commission, 2002; European Union, 2010). This high building energy consumption is due to deficient energy performance because HVAC systems are used for long periods to keep thermal comfort conditions inside dwellings. Consequently, other social problems are emerging, such as fuel poverty (Sánchez-Guevara Sánchez, Mavrogianni, & Neila González, 2017), so having solutions for high energy consumption could improve some aspects in various scopes, apart from the environmental one.

To lessen climate change, international goals should be established as the activities of each region greatly affect all over the world. In this regard, 195 countries were committed in the 2015 Paris Conference of the Parties (COP) to reduce greenhouse gas emissions (Tobin, Schmidt, Tosun, & Burns, 2018). Likewise, decarbonisation goals have been established by the year 2050 through various programs or policies, both at a continental (European Commission, 2011) and state scale (Climate Change Act, 2008, 2008; Ministry of the Environment (Japan) (2017)). Most of these policies establish a demanding goal: the reduction in building energy consumption by 90 % in comparison with the actual values.

Thus, designing efficient buildings is crucial. For this purpose, climate characteristics must be known, thus guaranteeing a sustainable built environment (Kim, Gu, & Kim, 2018). In addition, architects and engineers should know the microclimate conditions before and after constructing the building to ensure its sustainability (Stavrakakis et al., 2012). In short, both climate behaviour (Tejero-González, Andrés-Chicote, García-Ibáñez, Velasco-Gómez, & Rey-Martínez, 2016) and the vernacular architecture of the region (Manzano-Agugliaro, Montoya,

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https://doi.org/10.1016/j.scs.2021.103042
Received 3 February 2021; Received in revised form 5 May 2021; Accepted 21 May 2021

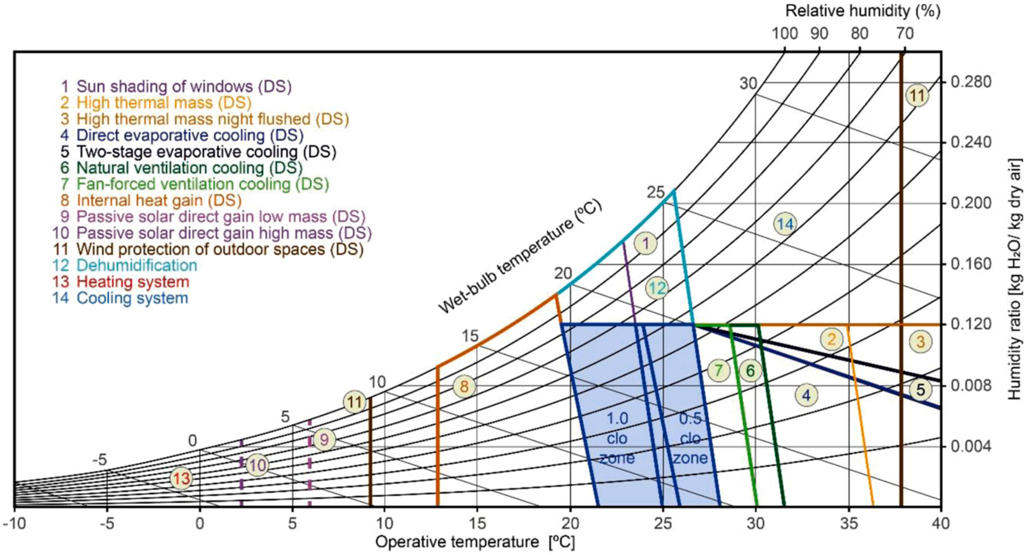


Fig. 1. Limits of the thermal comfort zone and the design strategies considered in the study.

Sabio-Ortega, & García-Cruz, 2015) should be known in detail to establish adapted design strategies. These design strategies adapted to climate imply many positive aspects: guaranteeing a great percentage of thermal comfort hours (Gaitani, Mihalakakou, & Santamouris, 2007) and reducing energy consumption (Casquero-Modrego & Goñi-Modrego, 2019), greenhouse gas emissions (Omer, 2008) and economic costs (Li, Yu, Liu, & Li, 2011; Taleb, 2014). Moreover, passive design strategies do not just affect buildings because they could be extrapolated to the urban scope. The most appropriate passive strategies in urban environments located in arid (Daemei, Azmoodeh, Zamani, & Khotbehsara, 2018; Hamdan & de Oliveira, 2019) or humid zones (Lu et al., 2017) have been studied.

The use of design strategies adapted to climate have been widely analysed: (i) Cicelsky and Meir (2014) determined that, in hot hyper-arid, the combination of extensive insulation, shade, high performance windows, air tightness and seasonal operation of window shutters ensures appropriate strategies for this type of climate; (ii) Khotbehsara, Daemei, and Malekjahan (2019) studied the energy performance of buildings located in four climates in Iran through the type of roof and determined the most appropriate passive design strategies; (iii) Asadi, Fakhari, and Sendi (2016) determined that bioclimatic techniques in Iran could avoid using air conditioning systems in summer; (iv) in another study conducted in the same region, Riahi Zaniani, Taghipour Ghahfarokhi, Jahangiri, and Alidadi Shamsabadi (2019) verified the great potential of using green roofs as passive strategy to reduce cooling demand; and (v) Yang, Fu, He, He, and Liu (2020) analysed the most appropriate design strategies in buildings located in Turpan (China). The most effective measures were passive solar heating in winter and the use of semi-basements and night ventilation in summer.

However, the effectiveness of these strategies in relation to climate change has been scarcely studied. Osman and Sevinc (2019) reported that resilient strategies should be focused on a more active cooling by 2070 in arid regions. However, climate change effects in other regions are unknown. Likewise, the studies analysing the influence of climate change scenarios have not considered the most recent climate change scenarios. Osman and Sevinc (2019) used the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC) (Intergovernmental Panel on Climate Change, 2007). Nevertheless, the SRES were updated through Representative Concentration Pathways (RCP) scenarios (Intergovernmental Panel on Climate Change, 2014). These RCP scenarios establish four tendencies of the evolution of greenhouse gas emissions throughout the 21 st century: a strict mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and a scenario with very high greenhouse gas emissions (RCP8.5). These scenarios have been hardly used to study the evolution of energy performance and thermal comfort and are focused on analysing their impact in terms of energy consumption (Cellura, Guarino, Longo, & Tumminia, 2018; Kikumoto, Ooka, Arima, & Yamanaka, 2015; Zhai & Helman, 2019). Thus, this paper analyses the influence of climate change on the design strategies adapted to climate. Thus, this study offers a new approach to the effectiveness of design strategies by considering RCP scenarios. In this regard, the lack of existing studies on RCP scenarios shows the need to analyze the effectiveness of energy improvements in the building stock. The analysis was mainly based on both the variation of the effectiveness of the design strategies to keep thermal comfort and the need for using HVAC systems. For this purpose, the climate zones existing in 6 countries were analysed: 3 developed countries (France, Portugal, and Spain) and 3 developing countries (Argentina, Brazil, and Chile). These countries were selected because of both the characteristics of their climate zones and their regulation on energy efficiency, very similar among them (Bienvenido-Huertas, Oliveira, Rubio-Bellido, & Marín, 2019). Each country stresses the importance of the envelope properties in building energy efficiency. However, design criteria are not established, so the results presented in this paper could be an opportunity for these countries to develop energy efficiency policies. Moreover, knowing the future effectiveness of design strategies leads to know the effectiveness of the energy policies today adopted (da Guarda et al., 2020). Likewise, the analysis was also based on the use of data mining algorithms, such as multilayer perceptrons and k-means, thus representing a new approach. In this regard, these techniques achieved appropriate results in energy analysis approaches (Fan, Ding, & Liao, 2019; Zhang, Cao, & Romagnoli, 2018) and estimated certain variables related to buildings under the effect of climate change (Li, (Jerry) Yu, Haghighat, & Zhang, 2019; Xia, Han, Zhao, & Liang, 2021).

2. Methodology

2.1. Determination of both design strategies and the percentage of thermal comfort hours

The methodology of this paper was based on the analysis of the existing climate data in each climate zone in each country to obtain generic design strategies. For this purpose, the comfort model defined in ASHRAE Standard 55, also known as the PMV (Predicted Mean Vote) model, was used because it is generally valid for an international approach (Bienvenido-Huertas, Rubio-Bellido, Pérez-Fargallo, &

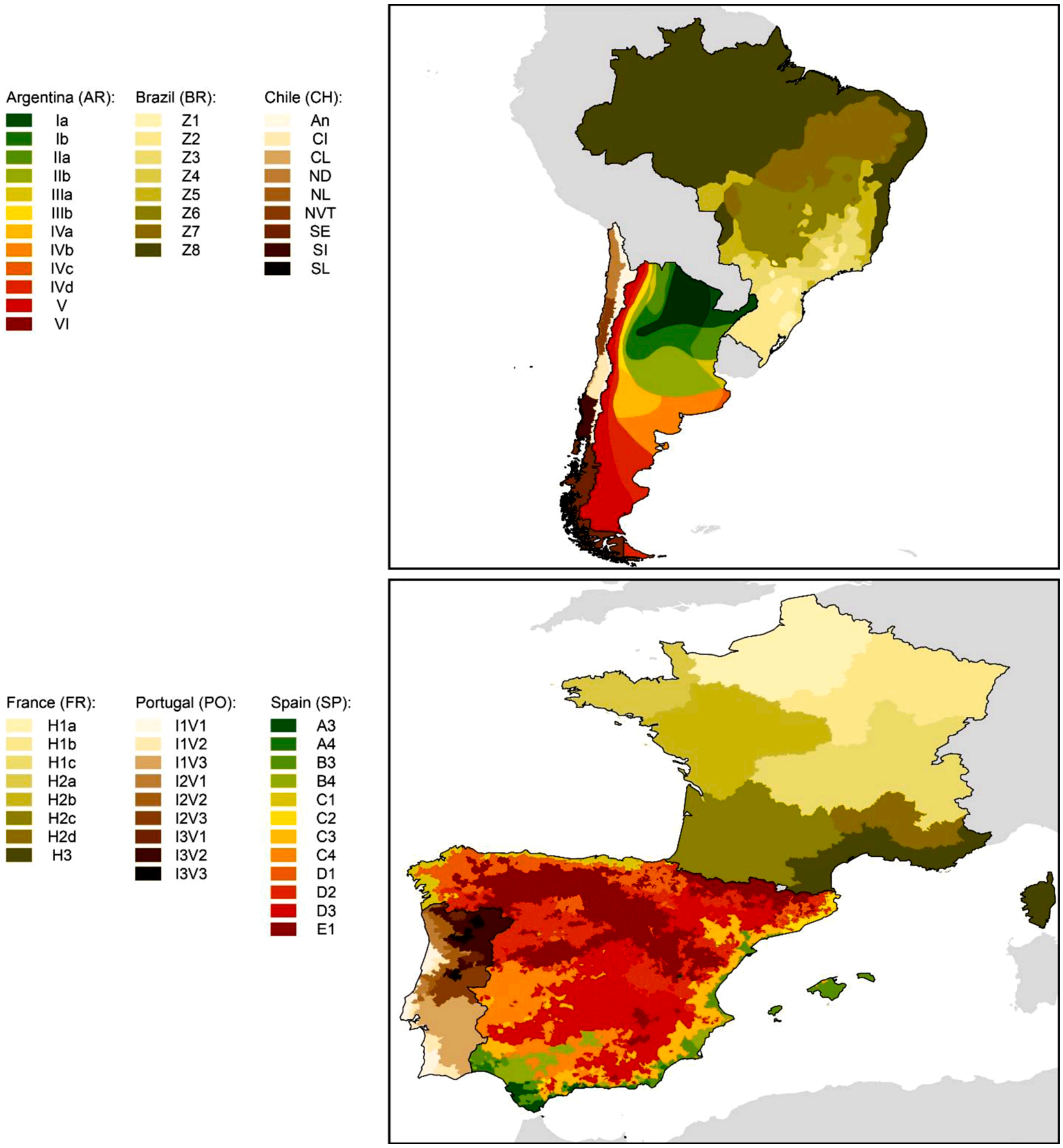


Fig. 2. Thermal zones in the 6 countries analysed in the study.

Pulido-Arcas, 2020). This model is an experimentally derived algorithm, which considers dry bulb temperature, humidity, air velocity, metabolic activity, and clothing insulation. All this climate variables can be depicted in a psychrometric chart to generate the 16 design strategies considered in the standard. This paper assessed the hourly data of each location (8760 h a year) within the strategies by using the Climate consultant tool. This tool was developed by Ligget and Milne of the Department of Architecture and Urban Design at the University of California (Los Angeles) (UCLA Energy Design Tools Group, 2018).

Several studies have used Climate Consultant to study architectural design strategies, but they are scarce. However, it has been recently more used: (i) Bougiatioti and Oikonomou (2020) used Climate Consultant to determine the possibilities of using passive strategies to improve thermal comfort in cold periods in the eastern Mediterranean; (ii) Khotbehsara et al. (2019) analysed the most appropriate passive design strategies in 4 climate zones in Iran; (iii) Osman and Sevinc (2019) determined the design strategies adapted in this research work for the current and future climate of Jartum (Sudan); (iv) Awad and Abd-Rabo (2020) studied the influence of the design strategies on thermal comfort in buildings in the United Arab Emirates; and (v) Gaber et al. (2020) concluded that the most appropriate design strategies for Alexandria are based on solar radiation and the air movement. For this purpose, they were based on the strategies determined through Climate Consultant. Likewise, Climate Consultant is of great interest to analyse certain climate variables (e.g., outdoor temperature or radiation), as some studies have shown: Cao, Bui, and Kjøniksen (2019), Costanzo and Donn (2017), Shafiee, Faizi, Yazdanfar, and Khanmohammadi (2020), and Daemei, Azmoodeh, Zamani, and Khotbehsara (2018).

In this study, Climate Consultant was used to determine both the most appropriate design strategy for the climate and the variation of the percentage of thermal comfort annual hours and of the percentage of hours when the use of HVAC systems was required. For this purpose, a psychometric diagram represents the increases in the thermal comfort zones by applying design strategies (DS). In addition, the thermal comfort model used was the model defined in ASHRAE 55-2017 (the predicted mean vote model) (ASHRAE, 2017). This model considered the dry-bulb temperature, relative humidity, air speed, and the metabolic activity. Moreover, the predicted mean vote model is determined

Table 1
Coordinates of the selected climate data in each zone.

Zone	Latitude	Longitude	Altitude	Zone	Latitude	Longitude	Altitude
AR-Ia	−29.467	−60.217	30	FR-H1A	48.857	2.351	62
AR-Ib	−27.954	−58.809	60	FR-H1B	47.902	1.904	105
AR-IIa	−28.568	−66.801	859	FR-H1C	45.187	5.726	215
AR-IIb	−31.392	−58.017	45	FR-H2A	47.655	−2.762	13
AR-IIIa	−32.750	−60.733	30	FR-H2B	47.084	2.396	152
AR-IIIb	−34.600	−58.382	0	FR-H2C	44.350	2.574	590
AR-IVa	−22.745	−65.897	3787	FR-H2D	44.735	4.599	305
AR-IVb	−37.894	−66.760	30	FR-H3	43.837	4.360	54
AR-IVc	−39.524	−69.280	473	PO-I1V1	37.328	−8.600	28
AR-IVd	−37.846	−58.256	143	PO-I1V2	38.524	−8.893	58
AR-V	−43.081	−68.307	120	PO-I1V3	38.573	−7.907	244
AR-VI	−47.412	−70.877	1440	PO-I2V1	41.149	−8.611	73
BR-Z1	−29.168	−51.179	535	PO-I2V2	41.533	−8.417	123
BR-Z2	−25.095	−50.162	850	PO-I2V3	39.823	−7.493	269
BR-Z3	−27.593	−48.553	150	PO-I3V1	40.536	−7.268	816
BR-Z4	−15.794	−47.883	1111	PO-I3V2	41.300	−7.740	607
BR-Z5	−23.961	−46.334	90	PO-I3V3	41.083	−7.867	864
BR-Z6	−16.679	−49.254	765	SP-A3	36.517	−6.283	0
BR-Z7	−8.087	−42.052	363	SP-A4	36.833	−2.450	0
BR-Z8	−1.456	−48.504	16	SP-B3	39.567	2.650	26
CH-An	−22.911	−68.200	2569	SP-B4	37.383	−5.983	17
CH-CI	−33.450	−70.667	486	SP-C1	43.367	−8.383	0
CH-CL	−33.046	−71.616	13	SP-C2	41.383	2.177	0
CH-ND	−22.462	−68.927	2341	SP-C3	37.178	−3.601	711
CH-NL	−23.646	−70.398	178	SP-C4	38.880	−6.975	196
CH-NVT	−30.017	−70.700	835	SP-D1	43.012	−7.557	393
CH-SE	−47.267	−72.550	910	SP-D2	40.965	−5.664	806
CH-SI	−38.529	−72.435	229	SP-D3	40.419	−3.692	681
CH-SL	−36.833	−73.050	49	SP-E1	40.654	−4.696	1121

by estimating the clothing used in winter and summer, i.e., it is characterised by defining two thermal comfort zones according to occupants' clothing insulation: zone of 0.5 clo (corresponding to the use of air conditioning systems) and zone of 1.0 clo (corresponding to the use of heating systems) (Fig. 1). It also considers that users are more comfortable with dryer air when temperatures are slightly higher. The use of this thermal comfort model allows both users' thermal comfort needs to be known and clothing to be changed according to the season (Kim, Tartarini, Parkinson, Cooper, & de Dear, 2019; Oh, Haberl, & Baltazar, 2020; Ryu, Hong, Seo, & Seo, 2017).

Through 11 design strategies, tolerances can be applied to each heating or cooling zone (Fig. 1). Design strategies between 2 and 7 increase the summer thermal comfort zone, and design strategies between 8 and 11 increase the winter thermal comfort zone.

2.2. *Climate zones and the obtaining of climate data*

This study analysed the climate zones in Argentina, Brazil, Chile, France, Portugal, and Spain because of the typical characteristics of the climate zones in each country, defined in their effective construction codes (Fig. 2). These zones encompass from very cold regions to very warm regions. In Argentina, the IRAM 11603 standard (Instituto Argentino de Normalización y Certificación, 2012) divides the climate of the country into 6 main zones: from the hottest (zone I) to the coldest (zone VI). In zones I-IV, there are 4 subcategories which better classify the various microclimates of the country: a (zones with thermal amplitudes greater than 14 °C), b (zones with thermal amplitudes lower than 14 °C), c (transition zones from zones with greater thermal amplitudes to other with lower thermal amplitudes), and d (coastal zones with low amplitudes throughout the year). The climate zones in Brazil are included in NBR 15220 (Associação Brasileira de Normas Técnicas, 2005), which divides the country into 8 zones according to the positions of the hourly records in the psychometric diagram. In Chile, one of the existing and recent climate classifications is included in the NCh 1079 standard (Instituto Nacional de Normalización (Chile) (2008)). This standard conducts a bioclimatic classification of the country in 9 zones, clearly influenced by the latitude and altitude of the zones in the country. In the European countries, climate classifications are based on the combination of two indicators which classify climate according to the type of winter and summer. In France, the climate classification is included in the RT2012 standard (Republique Française, 2010). This classification divides the country into 8 zones obtained by combining 3 winter zones (H1, H2, and H3) and 4 summer zones (a, b, c, and d). In Portugal, the climate classification is included in the decree-law 80/2006 (Ministério das Obras Públicas, 2006). Finally, the climate classification in Spain is included in the royal decree 314/2006 (The Government of Spain, 2006) and in its update with the royal decree 732/2019 (The Government of Spain, 2019). The classification distinguishes 5 winter zones (A, B, C, D, and E) and 4 summer zones (1, 2, 3, and 4) according to the degree days. Winter zones go from the less severe (zone A) to the most severe (zone E), and summer zones go from the less hot (zone 1) to the hottest (zone 4).

The climate data of each zone were obtained through METEONORM, a software composed of climate data from 8,325 weather stations divided throughout the planet and widely used (Bellia, Pedace, & Fragliasso, 2015; Hatwaambo, Jain, Perers, & Karlsson, 2009; Kameni et al., 2019), in both the current scenario and climate change scenarios. The coordinates of the selected locations in each zone are indicated in Table 1. The future climate data were obtained with 3 RCP scenarios: RCP 2.6 (low), RCP 4.5 (intermediate), and RCP 8.5 (high). Each scenario considers different evolution tendencies of the greenhouse gas emissions throughout the 21 st century: RCP 2.6 is the scenario closer to the fulfilment of the decarbonisation goals, and RCP 8.5 is the most unfavourable, with an increase in the global mean temperature between 2.6 and 4.8 °C. Climate data were obtained for each scenario in each decade of the 21 st century after the performance of this study (i.e., 2030, 2040, 2050, 2060, 2070, 2080, 2090, and 2100). A total of 25 climate data were obtained by each zone (1 from the current scenario, and 24 from future scenarios), resulting in 58 climate zones, so the climate data analysed in this study were 1,450. Each climate data was analysed with Climate Consultant, determining the percentage of thermal comfort hours and the needs for using HVAC systems with and without design strategies (Fig. 3). Thermal comfort assessment and the need for HVAC systems without design strategies are understood when

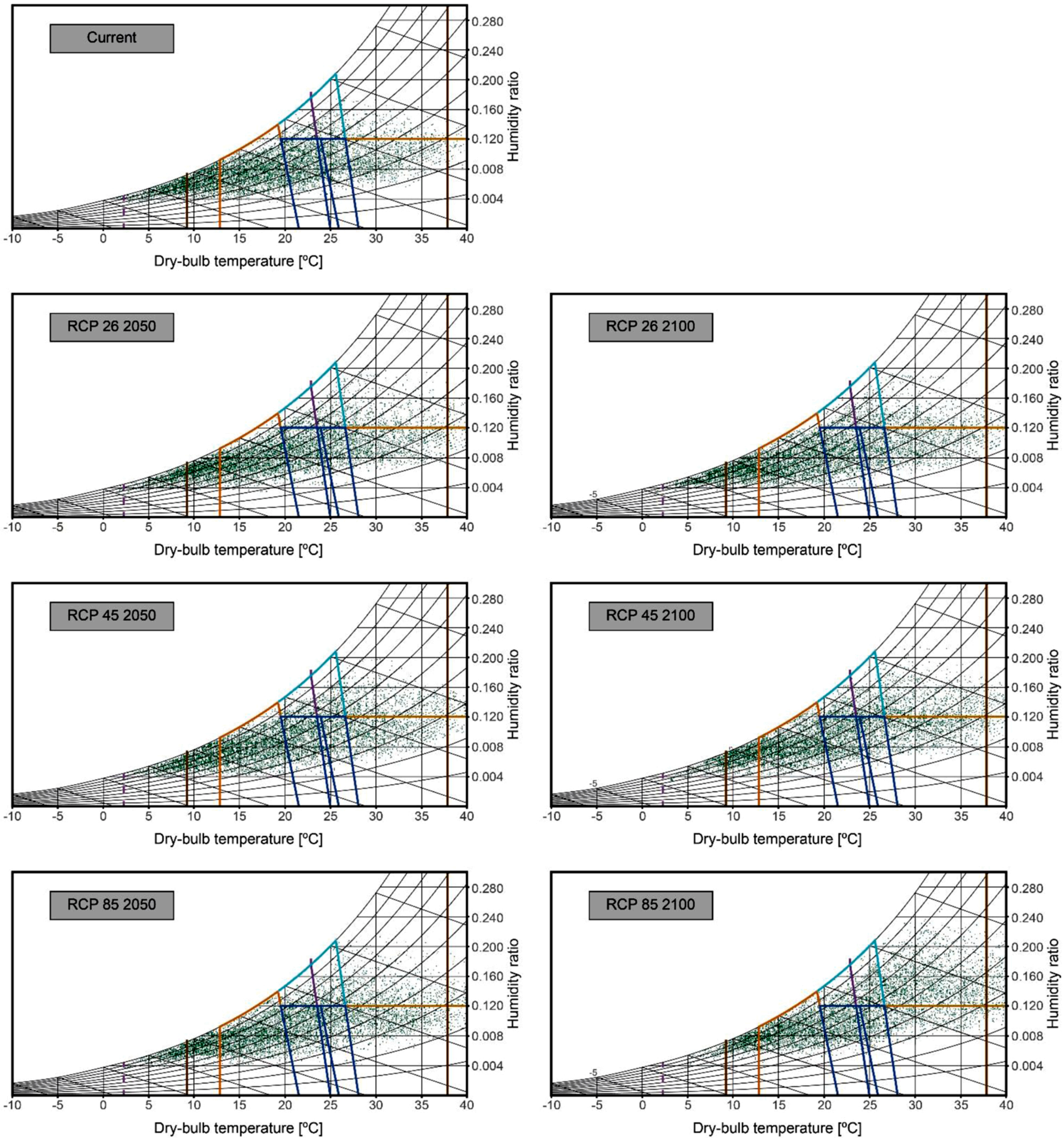


Fig. 3. Example of the analysis of the design strategies in the B4 thermal zone (Spain).

thermal comfort was assessed only for zones of 0.5 and 1.0 clo. As for the building assessment with design strategies, the increases in the thermal comfort limits were considered in the psychometric diagram with the optimal strategies determined by Climate Consultant.

2.3. Data mining

This study applied data mining approaches. The first approach was based on searching similarities among the climate zones analysed. For this purpose, cluster analyses were performed. The algorithm k-means was used like in other similar climate analysis studies (Bienvenido-Huertas, Sánchez-García, Rubio-Bellido, & Pulido-Arcas, 2021). This algorithm consists of grouping a set of individuals into k-groups. The algorithm begins with a random selection of k individuals from the dataset. Through the analysis of the Euclidean distances to the centroids, an iterative process is carried out until obtaining the optimal group (Hartigan & Wong, 1979). The value of k is therefore a key parameter in the grouping process. The elbow method is used to select the appropriate k-value. Through this method, the representation of the total within-cluster sum of squares allows the optimal value of k to be detected. This study used this method to determine the most appropriate input k-value. Likewise, the silhouette index was also used to define in detail the initial estimate of k obtained with the elbow method. The silhouette index ($s(i)$) is obtained through Eq. (1) and represents the similarity of each instance with the centroid to which it has been assigned. Thus, the analysis is individually performed in each dataset instance, and the average value represents the global level of the group.

Table 2
Input and output variable approaches analyzed for multilayer perceptrons.

Type	Output variable	Input variable
Without design strategies	Percentage of heating hours	Latitude, longitude, altitude, year, scenario
	Percentage of cooling hours	
	Percentage of dehumidification hours	
With design strategies	Percentage of heating hours	Latitude, longitude, altitude, year, scenario
	Percentage of cooling hours	
	Percentage of dehumidification hours	

The values obtained with this index oscillate between -1 and 1. Positive values indicate that the instance is in the correct group, while negative values indicate the opposite.

The variables considered in the cluster analysis were analysed with 3 dimensions according to the energy needs of each location: percentage of heating hours, percentage of cooling hours, and percentage of dehumidification hours. The analysis was carried out with the climate data of the current scenario and with those of the RCP 2.6, 4.5, and 8.5 scenarios in 2100.

$$s(i) = \frac{b(i) - a(i)}{max\{a(i), b(i)\}} \tag{1}$$

where $a(i)$ is the average distance between instance (i) and the remaining points of the same cluster; and $b(i)$ is the minimum average distance between the instance (i) and the remaining clusters.

Likewise, neural networks were used in the study. Their use was associated with the possibility of estimating the energy needs of each location through their coordinates. Although representative locations were selected for each climate zone, the availability of prediction tools allows energy needs to be estimated in other locations. This responds to the possible differences among the locations in the same climate zone (Bienvenido-Huertas et al., 2021). The neural network model used was the multilayer perceptron. This algorithm is characterized by its universal approximation capabilities (Barron, 1993; Cybenko, 1989; Hornik, Stinchcombe, & White, 1989), and is one of the most used algorithms in data mining approaches (Pino-Mejías, Pérez-Fargallo, Rubio-Bellido, & Pulido-Arcas, 2018; Pino-Mejías, Pérez-Fargallo, Rubio-Bellido, & Pulido-Arcas, 2017). The architecture of multilayer perceptrons is made up of an input layer, an intermediate layer, and an output layer. The independent variables are in the input layer, and the dependent variable in the output layer. Generally, models that only estimate a single variable are designed (Pino-Mejías et al., 2017, 2018). The multilayer perceptrons analysed are included in Table 2. Moreover, the models were trained by backpropagation (Rumelhart, Hinton, & Williams, 1986; Wang, 1994; Werbos, 1974) and using the Broyden-Fletcher-Goldfarb-Shanno algorithm (Fletcher, 1980). The quality of the estimates was statistically analysed with the coefficient of determination (R^2), the mean absolute error (MAE), and the root mean square error (RMSE):

$$R^2 = \left(1 - \frac{\sum_{i=1}^{n} (a_i - p_i)^2}{\sum_{i=1}^{n} (a_i - \overline{a}_i)^2}\right) \tag{2}$$

$$MAE = \frac{\sum_{i=1}^{n} |a_i - p_i|}{n} \tag{3}$$

$$RMSE = \left(\frac{\sum_{i=1}^{n} (a_i - p_i)^2}{n}\right)^{1/2} \tag{4}$$

where p_i is the predicted value, a_i is the actual value, and n is the number of instances in the dataset.

2.4. *Limitations of the study*

Some limitations should be considered when analysing the results. On the one hand, the thermal comfort model is not based on an adaptive behaviour pattern. The reason is the own limitations of the tool used to determine the design strategies. An adaptive use on the part of users would vary the thermal comfort limits established in ASHRAE 55-2017 in zones of 0.5 and 1 clo, so the percentage of hours to use HVAC systems could vary. On the other hand, this study does not consider the effect of possible urban heat islands (UHI). These phenomena cause that the air temperature in cities is higher than in the surroundings (Santamouris & Asimakopoulos, 1996). This aspect contributes to a greater cooling energy demand in buildings located within an UHI (Hassid et al., 2000; Salvati, Coch Roura, & Cecere, 2017), thus implying a greater risk for population (Sánchez-Guevara Sánchez, Núñez Peiró, Taylor, Mavrogianni, & Neila González, 2019).

3. Results and discussion

The analysis was first focused on the evolution of the thermal comfort hours. Table 3 shows the percentage values of the thermal comfort hours in the current scenario, Fig. 4 shows the percentage values obtained throughout the 21 st century with the three RCP scenarios, and Figs. A1–A6 show the time series. In the values obtained in the current scenario, appropriate design strategies adapted to climate significantly increased the percentage of thermal comfort hours in comparison with the buildings without those design strategies. The use of these measures implied an average increase of 41.48 %, with maximum increase values of 82 % (CH-ND). The effectiveness of the design strategies was reduced only in BR-Z7 and BR-Z8 because of the many hourly values with high temperatures and absolute humidity, which demanded the use of air conditioning systems. Nonetheless, the use of design strategies adapted to climate significantly increased the thermal comfort hours and reduced the use of HVAC systems (thus reducing its energy consumption). However, the effectiveness of the design strategies adapted to climate could varied throughout the 21 st century. Two aspects were crucial to know the variability presented by the percentage of thermal comfort hours: the RCP scenario and the type of climate zone. Thus, RCP 2.6 was characterised by having percentage variations close to zero. In this regard, the average annual values of the variations with RCP 2.6 oscillated between -0.38 and 0.50 % in buildings without design strategies, and between -0.66 and 0.37 % in buildings with design strategies. These percentage values caused that the tendencies of the time series of RCP 2.6 were almost horizontal with similar values in the current scenario and in 2100, with an average deviation of 0.40 %. Moreover, the effectiveness of the design strategies did not vary with RCP 2.6 in all the climate zones, obtaining very similar values to those obtained in the current scenario: an average increase value of 41.00 % in the thermal comfort hours and the same tendency detected in the climate zones, with the worst values in BR-Z7 and BR-Z8. This was due to the characteristics of RCP 2.6, which considers that the environmental policies are successful to reduce climate change effects.

However, the influence of climate change on the percentage of thermal comfort hours was detected in the other two scenarios. In RCP 4.5, the climate characteristics of each region could vary the percentages of thermal comfort hours. Thus, cold climate zones, such as those in Chile, increased the percentage of thermal comfort hours between 1.00

Table 3
Annual percentage of thermal comfort hours according to the design of the building in the current scenario.

Zone	Percentage of thermal comfort hours (without design strategies) [%]	Percentage of thermal comfort hours (with design strategies) [%]	Zone	Percentage of thermal comfort hours (without design strategies) [%]	Percentage of thermal comfort hours (with design strategies) [%]
AR-Ia	14	49	FR-H1A	10	46
AR-Ib	13	44	FR-H1B	10	42
AR-IIa	23	68	FR-H1C	11	46
AR-IIb	18	59	FR-H2A	7	46
AR-IIIa	16	55	FR-H2B	10	43
AR-IIIb	18	60	FR-H2C	9	43
AR-IVa	2	45	FR-H2D	14	52
AR-IVb	16	60	FR-H3	16	56
AR-IVc	15	56	PO-I1V1	20	68
AR-IVd	12	54	PO-I1V2	19	69
AR-V	7	40	PO-I1V3	17	63
AR-VI	4	39	PO-I2V1	12	63
BR-Z1	22	64	PO-I2V2	11	61
BR-Z2	18	68	PO-I2V3	18	61
BR-Z3	11	46	PO-I3V1	11	52
BR-Z4	34	73	PO-I3V2	12	52
BR-Z5	16	49	PO-I3V3	10	49
BR-Z6	30	66	SP-A3	20	64
BR-Z7	5	10	SP-A4	20	67
BR-Z8	0	0	SP-B3	10	47
CH-An	7	80	SP-B4	21	66
CH-CI	17	63	SP-C1	10	64
CH-CL	21	66	SP-C2	14	50
CH-ND	7	89	SP-C3	17	62
CH-NL	13	89	SP-C4	19	64
CH-NVT	4	57	SP-D1	7	48
CH-SE	6	44	SP-D2	12	48
CH-SI	9	42	SP-D3	19	62
CH-SL	8	52	SP-E1	13	50

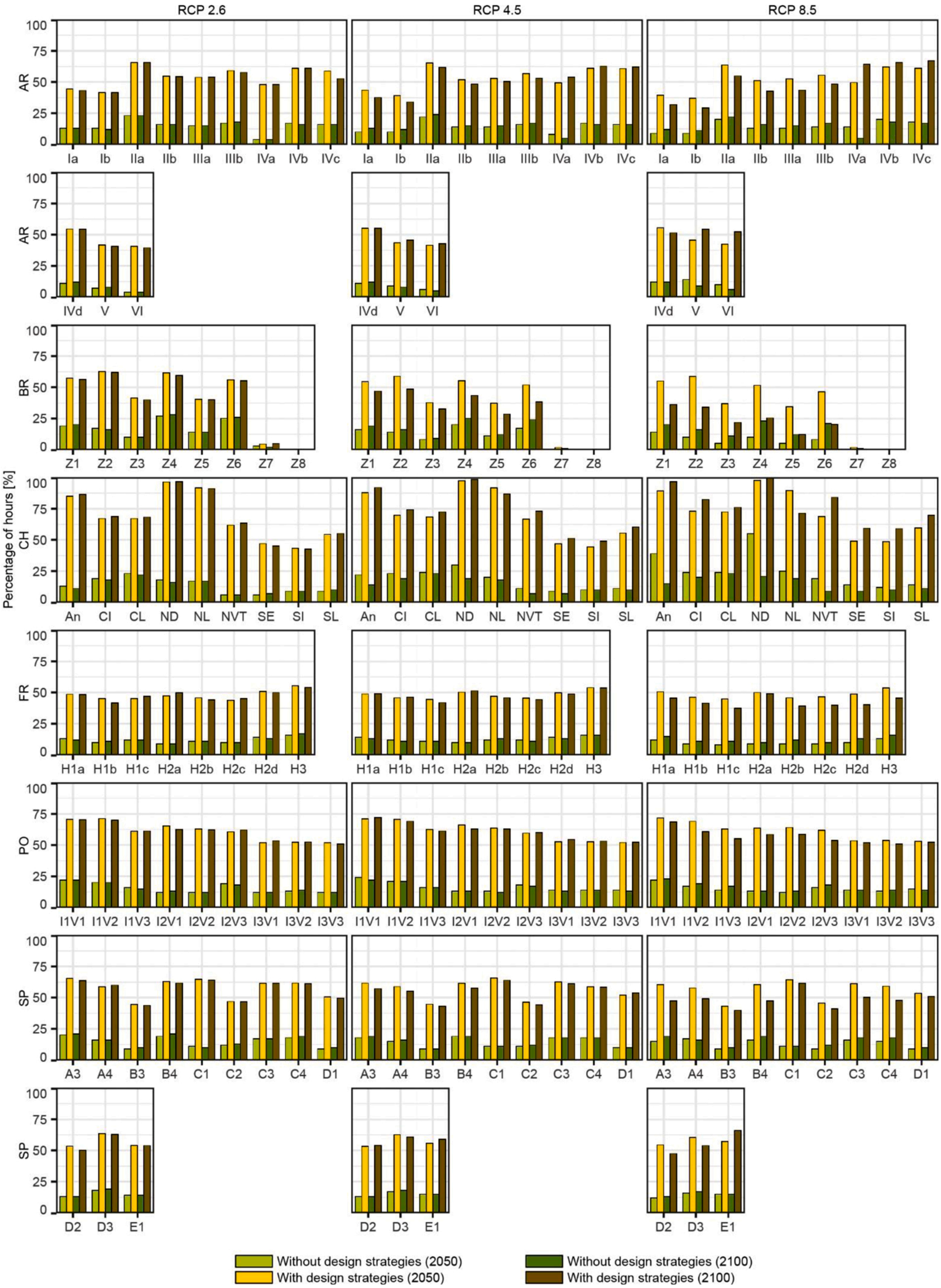


Fig. 4. Evolution of the percentage of thermal comfort hours according to both the design of the building and the climate change scenario.

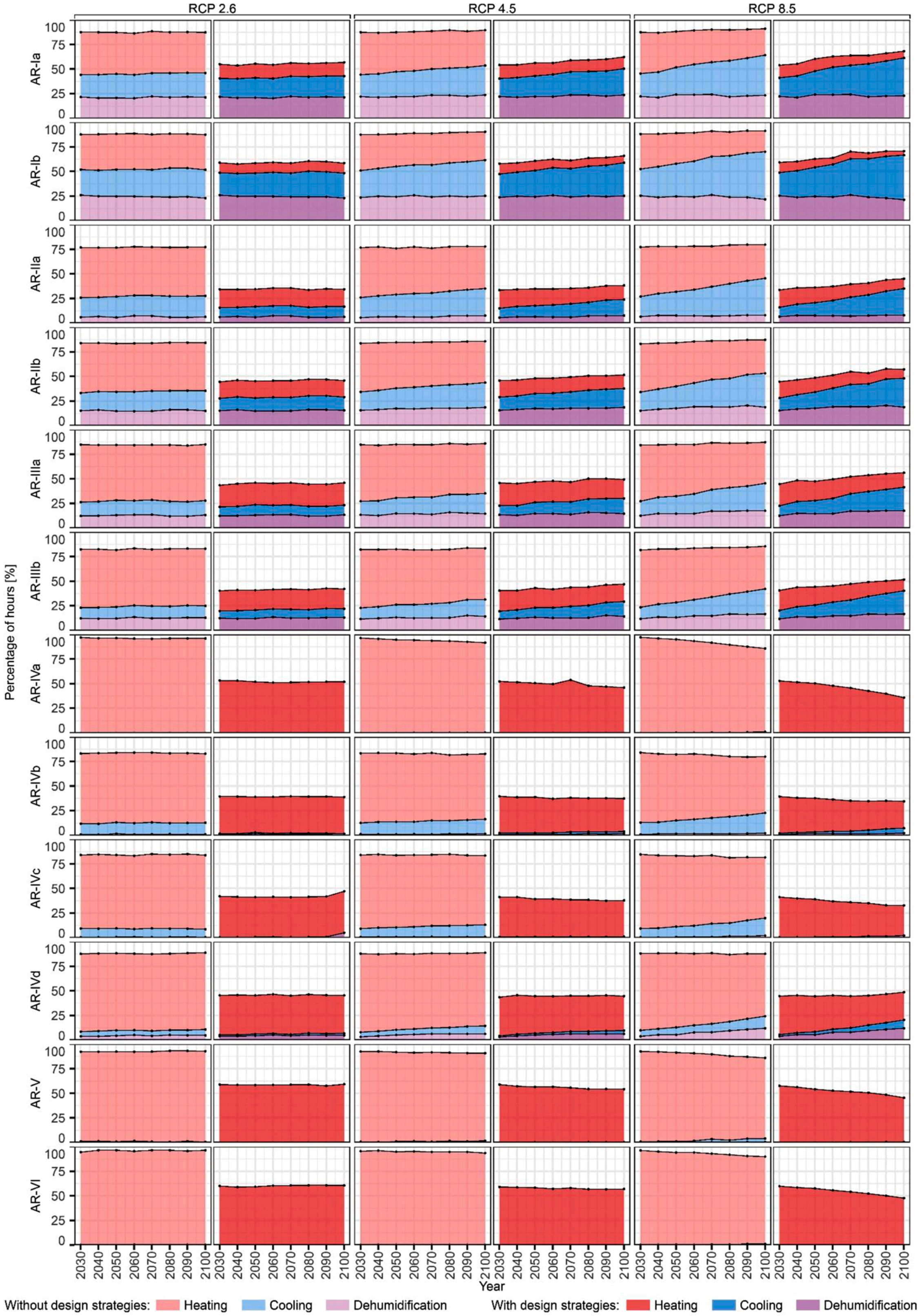


Fig. 5. Evolution of the percentage of hours with the need for using HVAC systems in Argentina according to both the building design and the climate change scenario.

and 16.00 % in the building without design strategies, and between 2.83 and 10.90 % in the building with design strategies, except CH-NL in which the percentage of thermal comfort hours was slightly reduced by 4.89 %. Likewise, in the cold climate zones in the other countries (AR-IVa, AR-IVb, AR-IVc, AR-V, AR-VI, FR-H1A, FR-H1B, FR-H2A, SP-D1, SP-D2, SP-D3, and SP-E1), the percentage of thermal comfort hours increased between 0.10 and 4.00 % in the building with design strategies, and between 0.38 and 6.18 % in the building with design strategies.

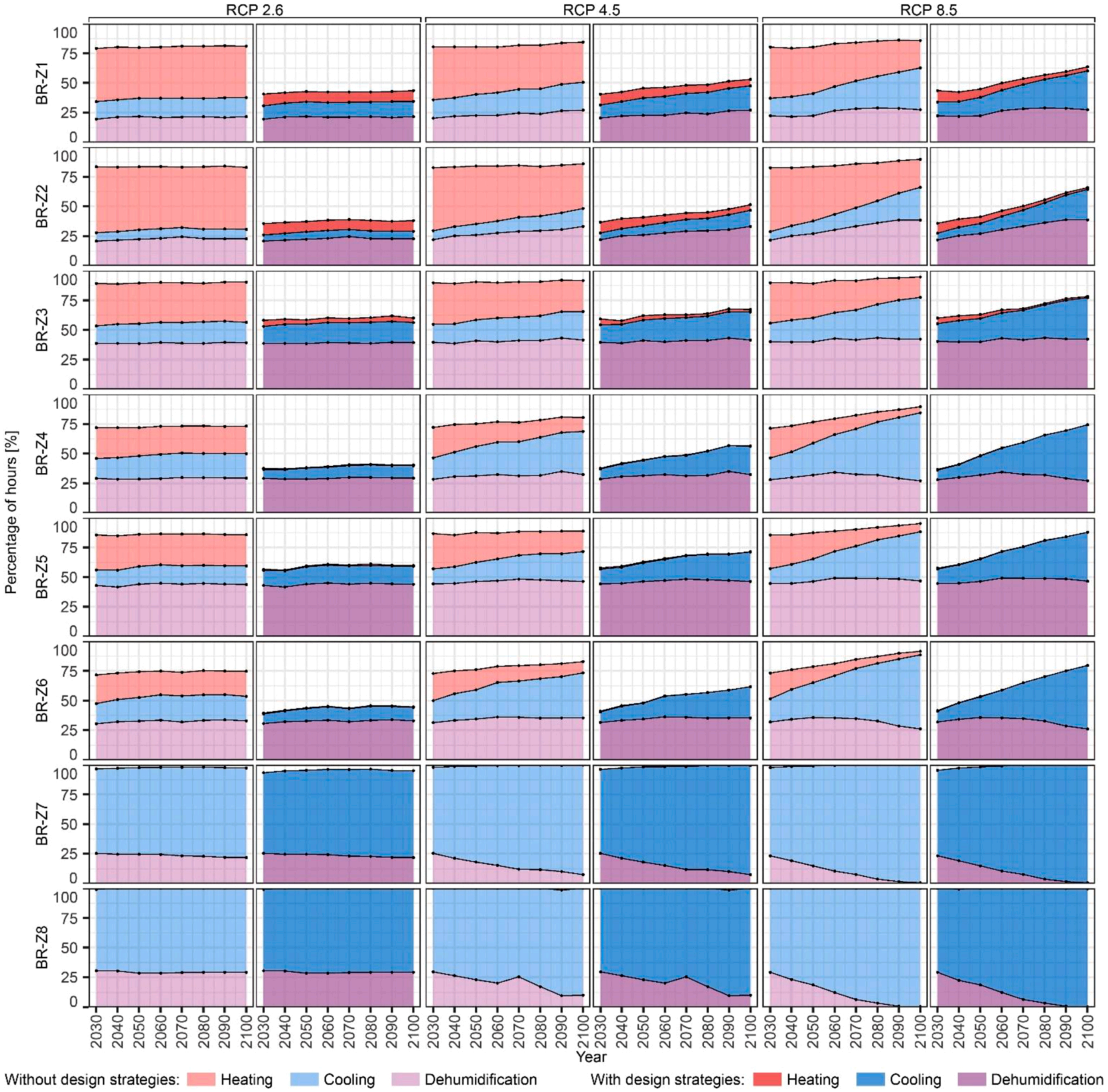


Fig. 6. Evolution of the percentage of hours with the need for using HVAC systems in Brazil according to both the building design and the climate change scenario.

However, the climate zones with a lower heating energy demand in the current scenario obtained a worse percentage of thermal comfort hours. In this regard, the average decrease percentage at the end of the century was 1.36 % for the two designs (with and without design strategies), with maximum decrease values of up to 20.55 % in BR-Z6. On the other hand, RCP 8.5 presented the same variation tendencies, although significantly reduced the thermal comfort hours between the current scenario and the year 2100 in the less cold zones. Thus, there was an average decrease of the percentage of thermal comfort hours of 3.39 %, with maximum values up to 38.04 %. However, the percentage of thermal comfort hours were considerably improved in the cold zones, reaching increase values of 29.00 % (CH-An) and 42.00 % (CH-ND).

Moreover, it is worth stressing the effectiveness loss detected with the design strategies in RCP 4.5 and RCP 8.5 throughout the 21 st century. In all the climate zones with RCP 2.6, the effectiveness of the design strategies varied the thermal comfort hours between -4.99 and 1.18 % at the end of the century, and in RCP 4.5 and 8.5, these tendencies varied according to the climate zone. In the cold climate zones, the design strategies increased the improvement of the thermal comfort hours at the end of the 21 st century in comparison with the building without design strategies, ranging this increase between 0.24 and 5.90 % in RCP 4.5, and between 0.90 and 12.33 % in RCP 8.5. However, in the other zones the effectiveness of the design strategies was clearly reduced in the thermal comfort hours at the end of the century between 0.17 and 13.17 % in RCP 4.5, and between 1.45 and 37.57 % in RCP 8.5.

As expected, climate change varied the thermal comfort hours in buildings with and without design strategies. However, the distribution of the need for using HVAC systems in the hours out the thermal comfort limits should be analysed. For this purpose, the percentage of hours of three aspects was analysed: heating, cooling, and dehumidification. It is worth mentioning that, due to the characteristics of the thermal comfort model used, humidification of the indoor environment was not considered. Figs. 5–10 showed the tendencies of the percentage of hours when

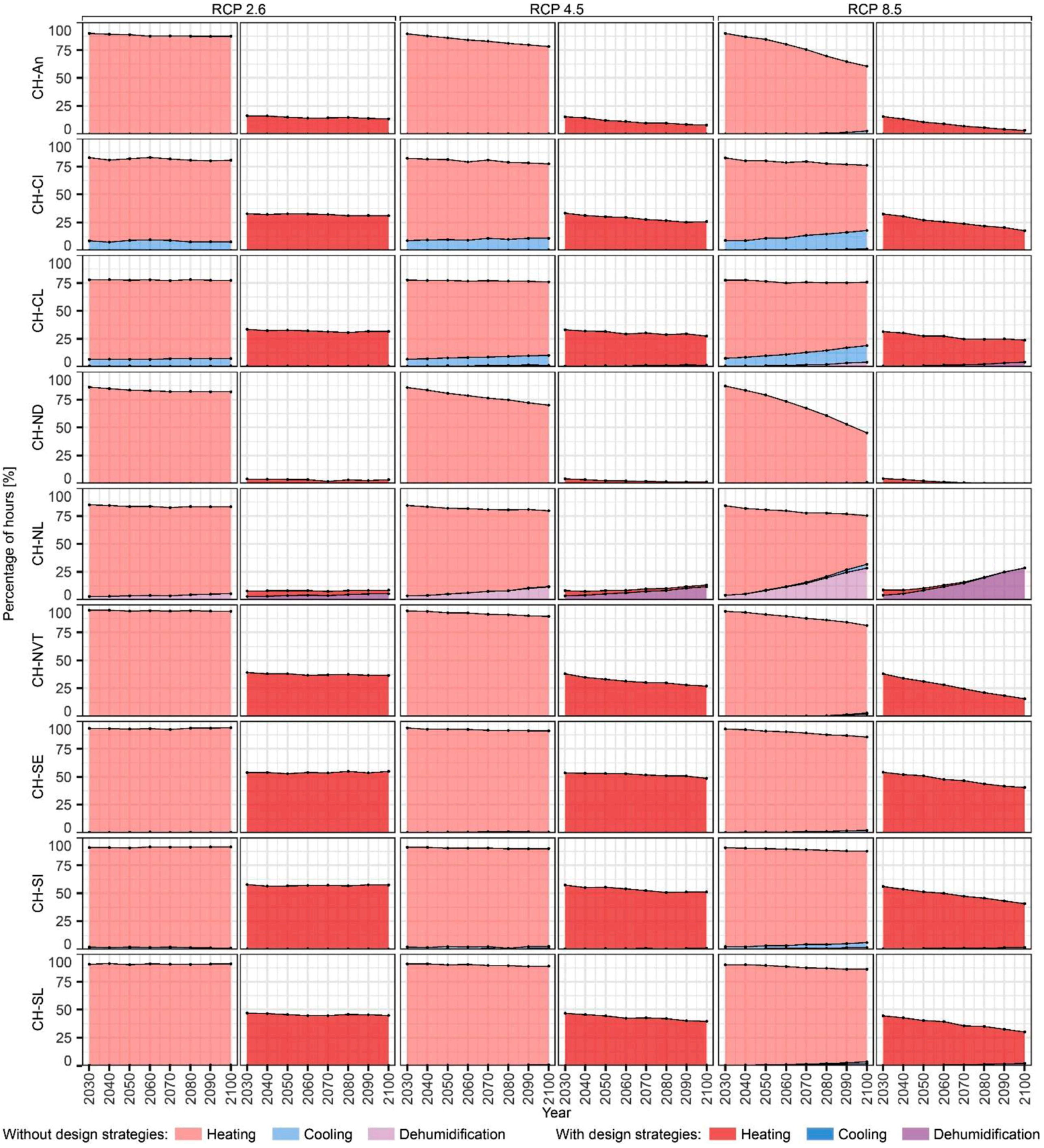


Fig. 7. Evolution of the percentage of hours with the need for using HVAC systems in Chile according to both the building design and the climate change scenario.

the use of HVAC systems was required, making distinctions according to whether the building had design strategies appropriate for the climate. The climate zones in each country presented clear characteristics of cooling demand, and the cold climate zones in Chile and Argentina only had heating energy demand; in Brazil, however, there were zones with a high percentage of cooling and dehumidification hours. In the other zones, heating, cooling, and dehumidification hours were distributed. The climate change effect could modify the percentage values. Like in the percentage of thermal comfort hours, this modification depends on the type of climate change scenario. RCP 2.6 was the scenario less affecting the variation of the percentage values, with modifications at the end of the century oscillating between 1 and 5% in cooling, between 2 and 6% in heating, and between 2 and 4% in dehumidification, both in buildings with and without design strategies. The effectiveness of the design strategies was invariable, with an average percentage saving value in hours with the need for using HVAC systems of 41 % and maximum values up to 80 %. However, in RCP 4.5 and 8.5, the energy requirements presenting the same tendency changed: (i) decrease in heating hours, (ii) increase in cooling hours, and (iii) increase and decrease in dehumidification hours according to the climate. These tendencies are more stressed in RCP 8.5. The following values were obtained in the building without design strategies: (i) an average decrease in heating of 7% with RCP 4.5, and of 17 % with RCP 8.5; (ii) an average increase in the percentage of cooling hours of 5% with RCP 4.5,

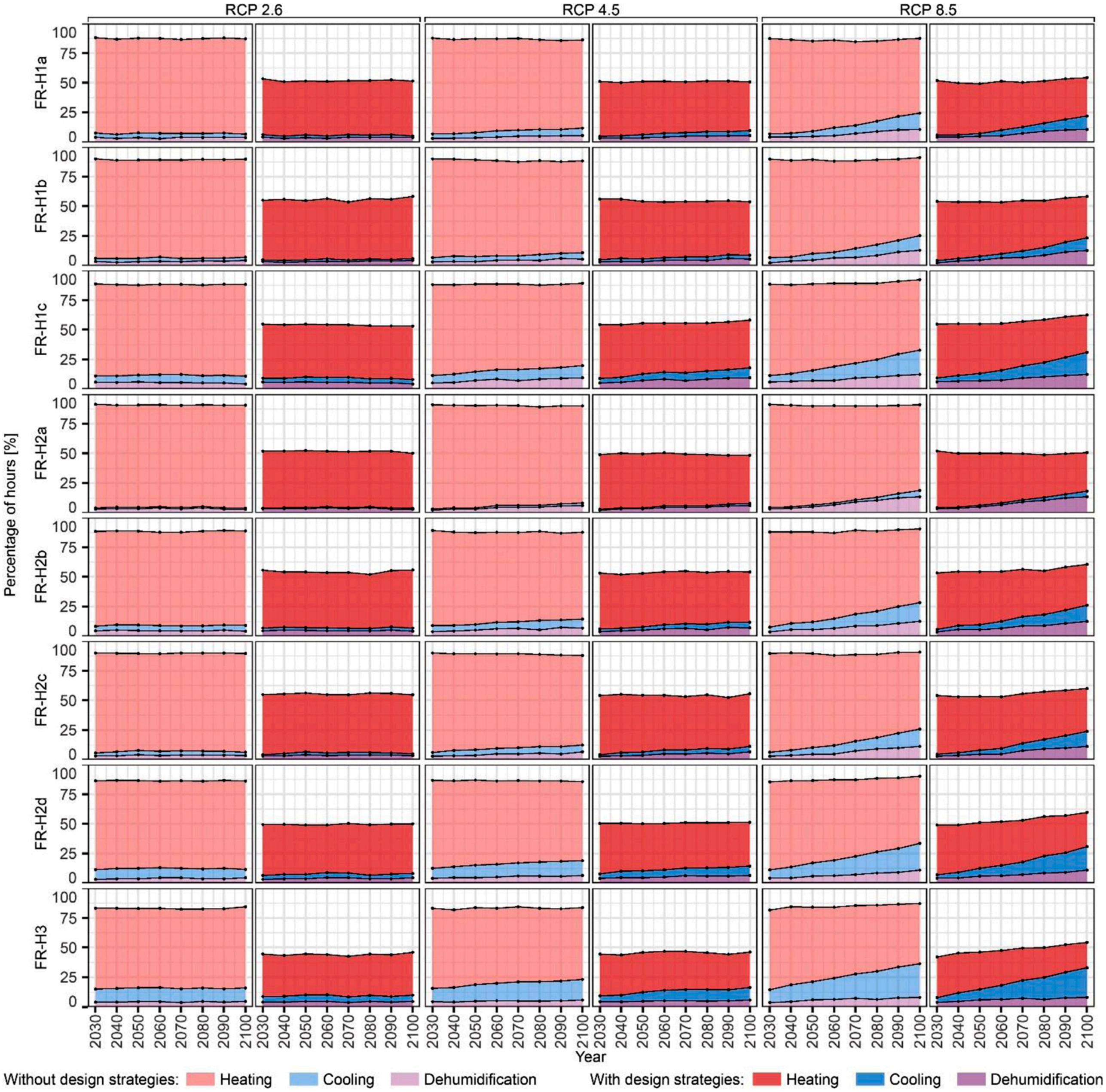


Fig. 8. Evolution of the percentage of hours with the need for using HVAC systems in France according to both the building design and the climate change scenario.

and of 13 % with RCP 8.5; and (iii) the percentage of dehumidification hours presented variations between -20 and 11 % in RCP 4.5, and between -29 and 24 % with RCP 8.5. Thus, it is expected that the energy requirements vary in the future if decarbonisation policies are not fulfilled, with greater cooling energy demand. This could mean an effectiveness loss of the design strategies adapted to the climate due to the limitations to achieve thermal comfort with both a high operative temperature and high absolute humidity. In this regard, the design strategies presented a greater saving in heating hours (an average saving of 36 %) than in cooling hours (an average saving of 4%), so the effectiveness of the saving achieved with the design strategies was reduced in comparison with the building without design strategies due to the increase in the energy cooling requirements with RCP 4.5 and 8.5.

Thus, the decrease in design strategies throughout the RCP scenarios could suggest the need to establish effective design policies in each country. However, these policies could be adopted with international criteria to guarantee a faster achievement of the existing low-carbon goals. In this regard, the establishment of similarities among the climate zones could be helpful to establish similar design criteria among the different regions. For this purpose, a cluster analysis based on k-means was carried out through a three-dimensional approach with the following variables: percentage of heating hours, percentage of cooling hours, and percentage of dehumidification hours. The analysis was independently performed for the current scenario and for the 2100 RCP scenarios (Fig. 11). The number of k in each analysis was always 5. The suitability of the classifications was shown in the silhouette index obtained: it was greater than 1 in most cases (except in RCP 2.6 and in RCP 8.5, in which a poorly classified area was obtained). In the current scenario, the following groups were obtained: (i) group 1 was made up of zones BR-Z7, and BR-Z8; (ii) group 2 was made up of zones AR-IVb, AR-IVc, CH-CI, CH-CL, FR-H2d, FR-H3, PO-I1V1, PO-I1V2, PO-I1V3, PO-I2V3, SP-C3, and SP-D3; (iii) group 3 was made up of zones AR-IIa, AR-IIb, AR-IIIa, AR-IIIb, BR-Z1, BR-Z2, SP-A3, SP-A4, SP-B3, SP-B4, SP-C2, and SP-C4; (iv) group 4 was made up of zones AR-Ia, AR-Ib,

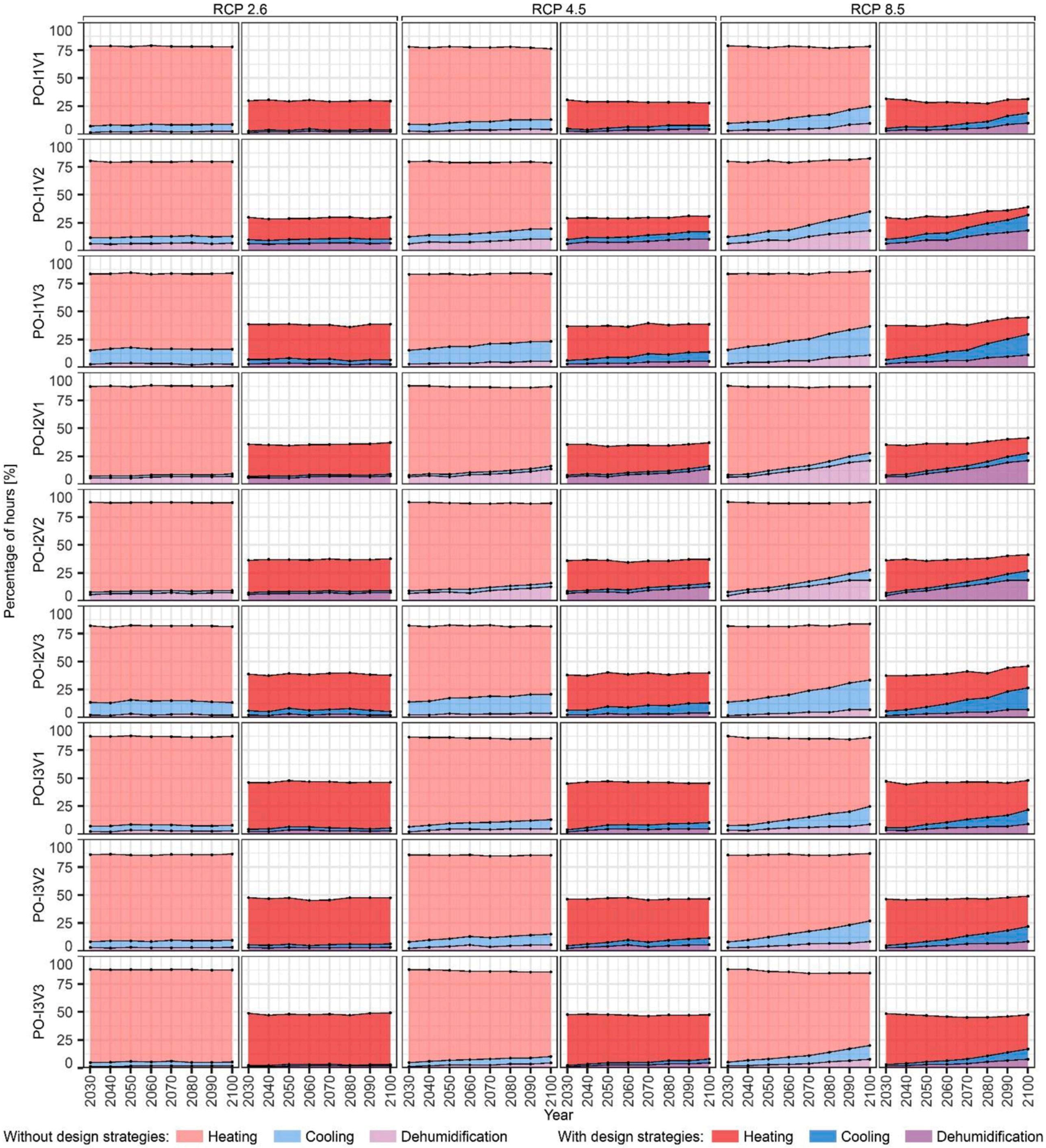


Fig. 9. Evolution of the percentage of hours with the need for using HVAC systems in Portugal according to both the building design and the climate change scenario.

BR-Z3, BR-Z4, BR-Z5, and BR-Z6; and (v) group 5 was made up of zones AR-IVa, AR-IVd, AR-V, AR-VI, CH-An, CH-ND, CH-NL, CH-NVT, CH-SE, CH- SI, CH-SL, FR-H1a, FR-H1b, FR-H1c, FR-H2a, FR-H2b, FR-H2c, PO-I2V1, PO-I2V2, PO-I3V1, PO-I3V2, PO-I3V3, SP-C1, SP-D1, SP-D2, and SP-E1. These 5 groups had a clear three-dimensional border in the current scenario shown by the values of the centroids of each group (Table 4). Group 1 corresponded to the warmest zones with the highest cooling demand in Brazil, and group 5 corresponded to the coldest zones with the highest heating energy demand. However, these borders varied at the end of the 21 st century according to the RCP scenario. The reason was the increased cooling energy demand (particularly in RCP 4.5 and 8.5). This aspect changed the group to which the zones belonged, particularly between clusters 2 and 5. This variation implied a partial modification of the centroids: an increase in the percentage of cooling hours, and a decrease in the percentage of heating and dehumidification hours. Thus, an adaptive perspective is required to establish design criteria for buildings. These groups are an opportunity for the governments of these countries. Likewise, the similarities detected among the zones could facilitate the establishment of synergies between countries to define the most appropriate sustainable design strategies for each region.

Another key aspect to establish measures based on the future is the possibility of having methodologies to estimate the energy demands of a location. The cluster analysis has shown that the groups of the current

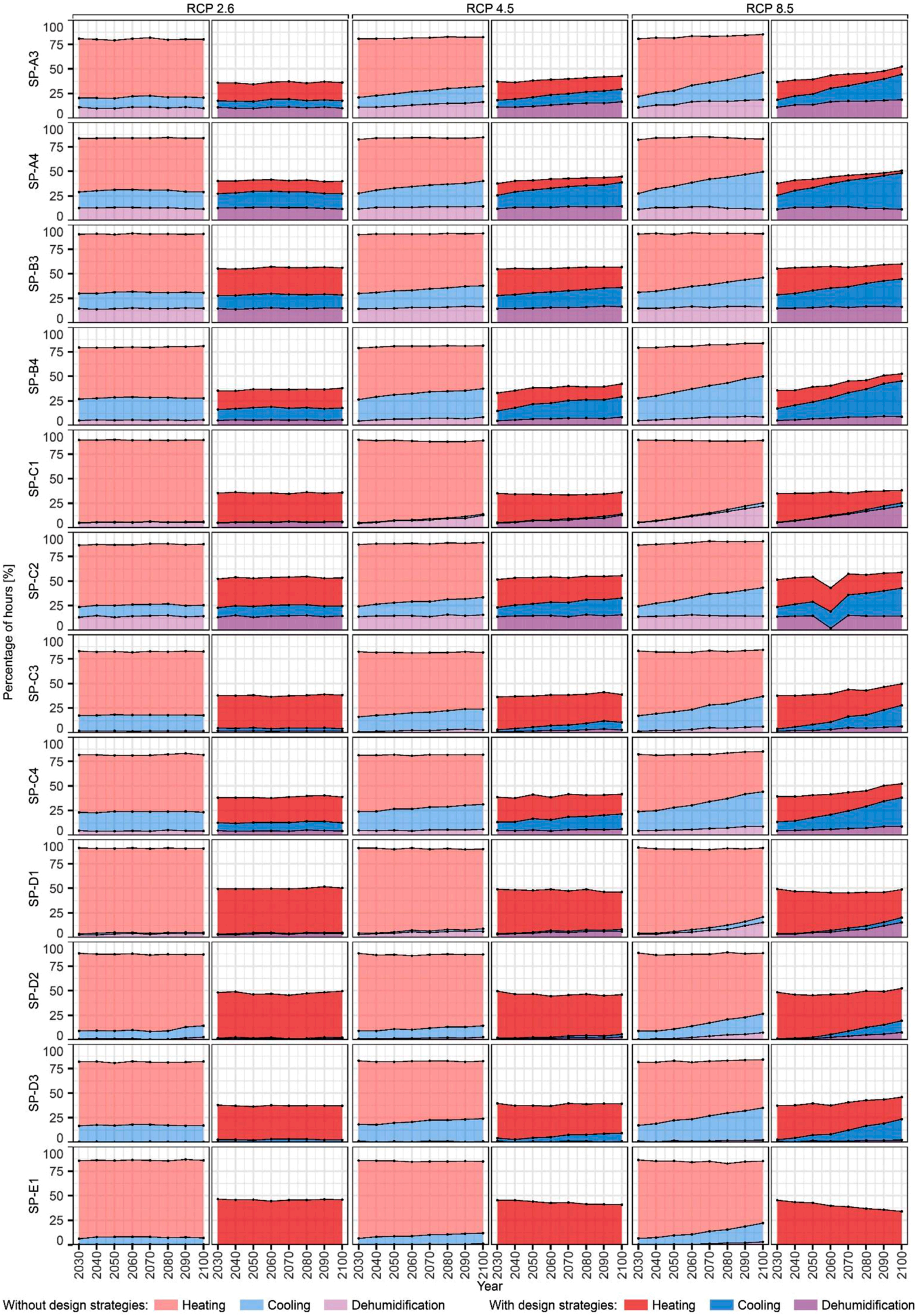


Fig. 10. Evolution of the percentage of hours with the need for using HVAC systems in Spain according to both the building design and the climate change scenario.

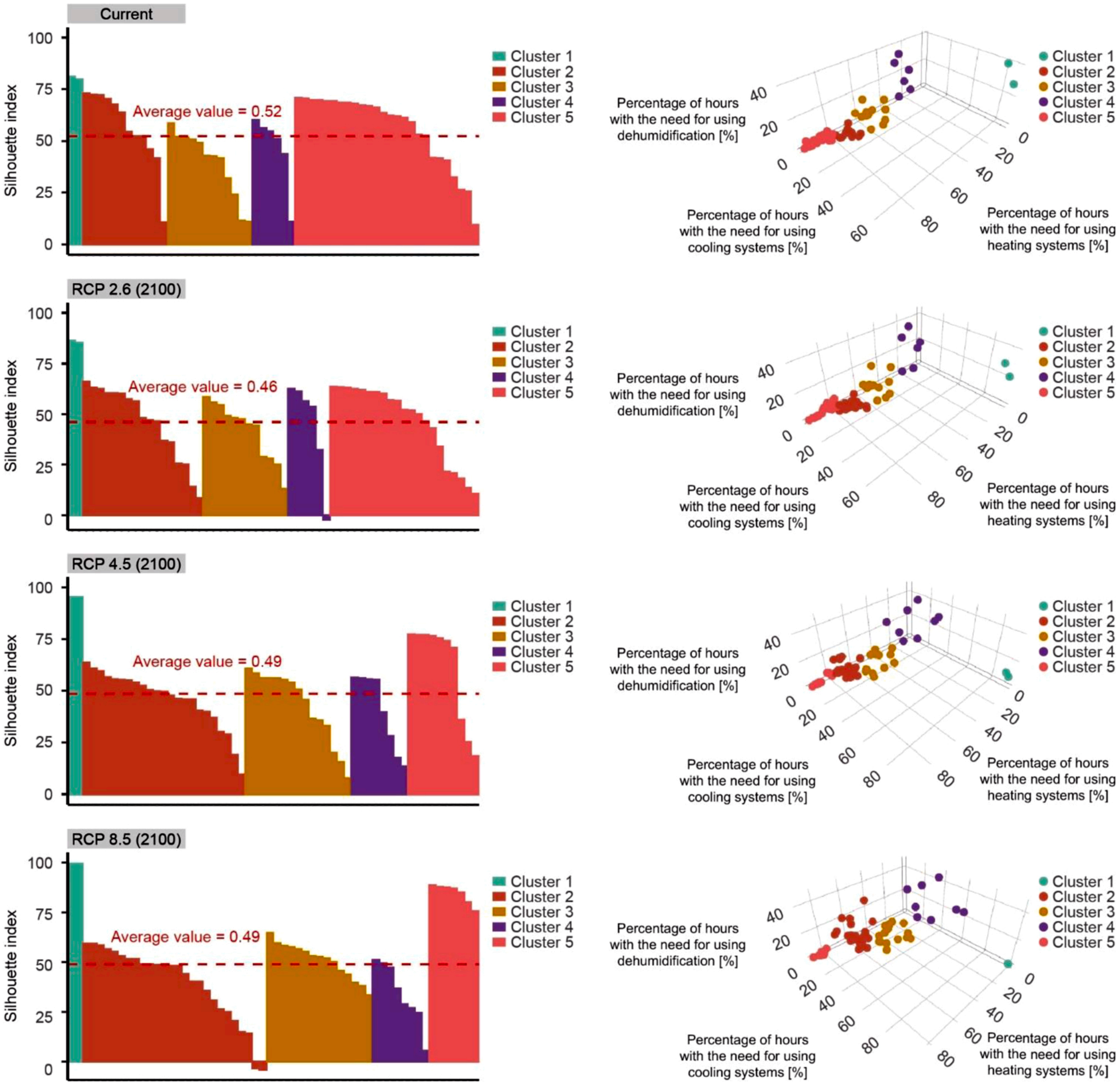


Fig. 11. Results obtained from the cluster analysis. The silhouette index values are shown on the left, and the three-dimensional distribution of the analysed zones on the right.

Table 4
Results obtained in the statistical parameters of the multilayer perceptrons.

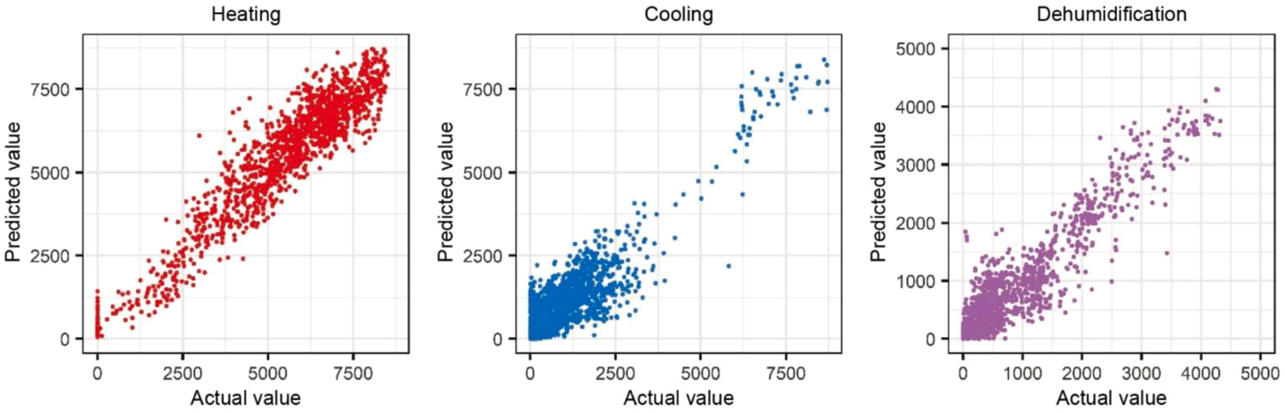
Parameter	Without design strategies			With design strategies		
	Percentage of heating hours	Percentage of cooling hours	Percentage of dehumidification hours	Percentage of heating hours	Percentage of cooling hours	Percentage of dehumidification hours
R^2	94.13	90.30	92.89	95.93	93.62	92.92
MAE	6.11	5.30	3.01	3.72	4.22	2.99
RMSE	7.74	6.96	4.02	4.72	5.67	4.02

scenario could vary throughout the 21 st century. Therefore, a complementary methodology should estimate the energy needs of any location. This aspect responds to the need detected in some studies using climate zones because the energy requirements of locations in the same climate zone could vary (Bienvenido-Huertas et al., 2021). This study therefore considered the possibility of using multilayer perceptrons. The multilayer perceptrons were designed using the latitude, longitude, and altitude of each location as input variables, as well as the year and the setting to be characterized. With this approach of input variables, independent models were developed for the percentage of hours when HVAC systems should be used, regardless of whether the building has an effective design or not. Table 5 shows the results obtained in the statistical parameters, and Fig. 12 shows the point clouds between the actual and estimated values. As a result, the quality of the estimates was

Table 5
Centroids and number of zones associated with each cluster.

Scenario	Cluster	Centroid			Number of zones
		Percentage of cooling hours [%]	Percentage of heating hours [%]	Percentage of dehumidification hours [%]	
Current	1	63.68	0.00	33.83	2
	2	8.27	72.54	1.73	12
	3	12.86	58.28	10.67	12
	4	15.89	36.10	28.24	6
	5	1.64	87.46	1.86	26
RCP 2.6 (2100)	1	73.20	0.00	25.50	2
	2	9.36	71.54	2.65	17
	3	15.69	54.70	12.82	12
	4	21.30	30.22	31.65	6
	5	1.46	85.73	2.60	21
RCP 4.5 (2100)	1	91.23	0.00	8.69	2
	2	7.52	70.41	5.99	23
	3	21.43	52.17	10.20	15
	4	28.59	25.03	33.15	8
	5	1.02	86.94	1.40	10
RCP 8.5 (2100)	1	99.44	0.00	0.56	2
	2	12.88	59.71	10.65	26
	3	31.36	42.54	11.67	15
	4	43.54	15.89	31.73	8
	5	2.12	83.05	0.91	7

Without design strategies



With design strategies

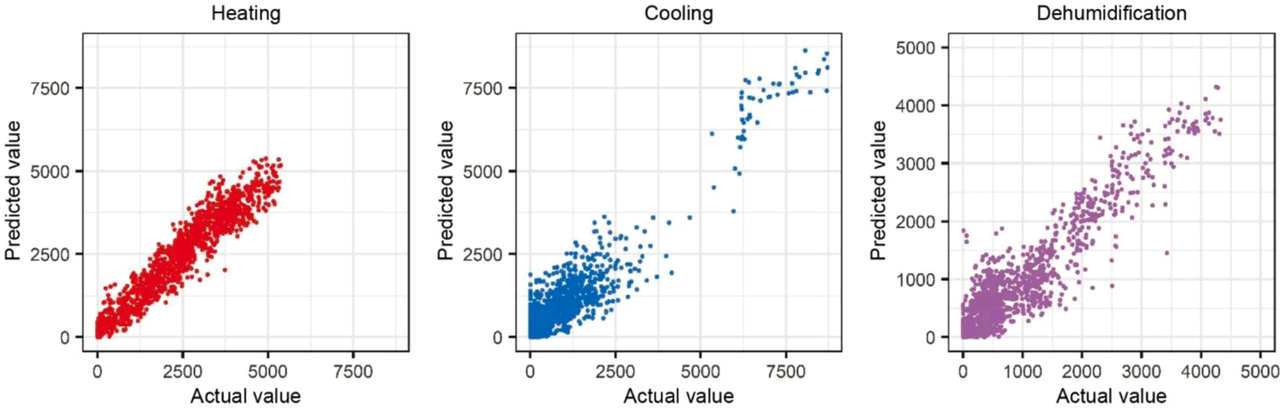


Fig. 12. Point clouds between the actual values and the values predicted by the multilayer perceptrons.

appropriate. Moreover, the coefficient of determination was always greater than 90 %, with values in some cases close to 95 %. Likewise, the percentage of error ranged between 2.99 and 6.11 % in MAE, and between 4.02 and 7.74 % in RMSE. Thus, the estimated values were close to the actual values, so multilayer perceptrons could be used by architects, technicians, and policy makers to have a more extensive knowledge of the energy requirements of any location. This would avoid the need for a detailed analysis of each climate characteristic.

It is worth stressing that the approach of the building with design strategies was determined based on the existing climate data in the current scenario, thus reproducing the behaviour of future buildings designed by architects and engineers. However, architects and engineers

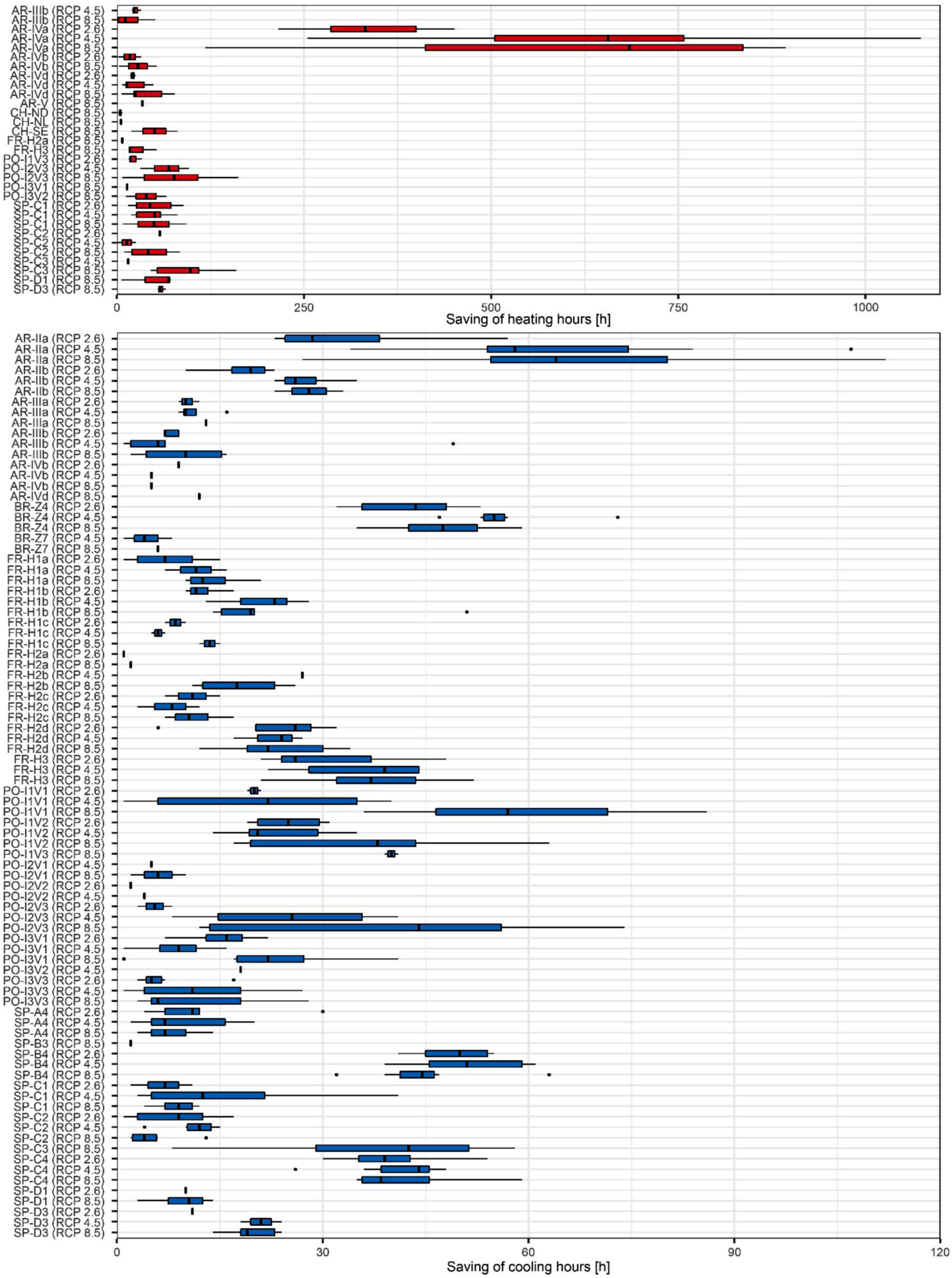


Fig. 13. Box-plots with the saving in heating and cooling hours between the performance of the building with design strategies of the current scenario in the future and the optimisation of the design strategies adapted to future years.

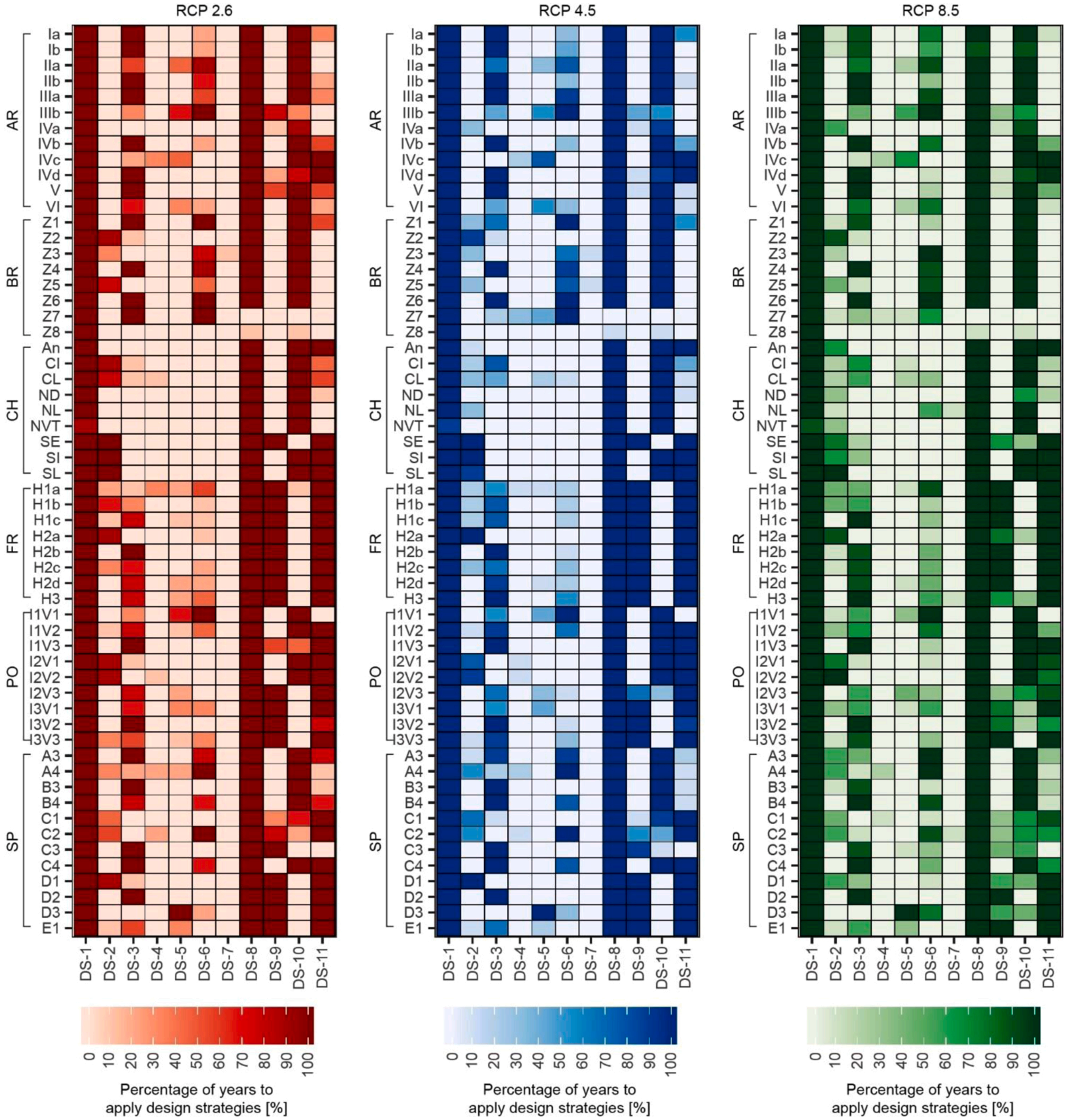


Fig. 14. Percentage of years to apply the design strategies throughout the 21 st century, adapting them to the climate variations of each RCP scenario in the climate zones in Argentina.

could use future climate scenarios to determine the most appropriate design based on future climate variations. For this reason, the variation of the hours using HVAC systems was analysed in buildings with design strategies adapted to the climate change scenario. Fig. 13 shows the distributions of the saving obtained in heating and cooling hours (the saving in dehumidification hours was not included as they were not obtained with the design strategies adapted to climate change). The optimisation of design strategies affected more zones to save cooling hours than heating hours. The number of heating zones with possibility of reducing heating hours was 20, and the number of zones with possibility of reducing cooling hours was 34. Nevertheless, the quartile values of the saving in heating hours were greater than in cooling. This corresponded to the tendency with greater effectiveness of the design strategies to reduce the heating energy demand instead of cooling energy demand. Regarding the possible variation of the design strategies, Fig. 14 shows the annual percentage of application of the design strategies adapted to each design, i.e., the percentage value to apply design strategies in the decades of the 21 st century. As indicated in Section 2, the design strategies increased the limits associated with the thermal comfort zones of both 0.5 and 1.0 clo from ASHRAE 55-2017. Thus, the use of these design strategies covered more thermal comfort hours than in the case of not having these strategies. The selection of the strategies was optimized to use as less number as possible of strategies with the greatest percentage of thermal comfort hours. The design strategies varied according to the type of climate, with the common aspect of the prevalence of solar protection (DS-1). Thus, the design strategies based

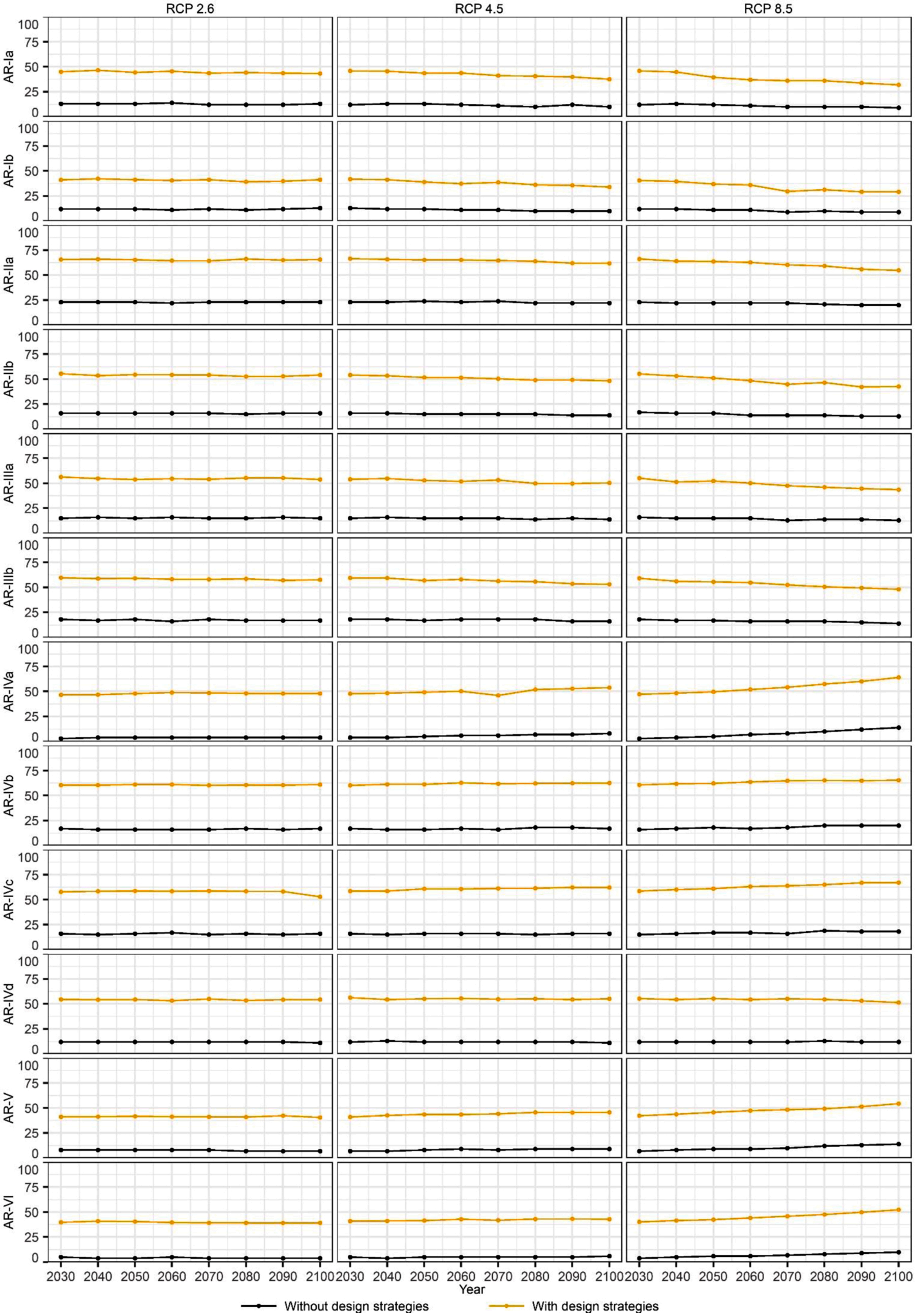


Fig. A1. Evolution of the percentage of thermal comfort hours in Argentina according to both the design of the building and the climate change scenario.

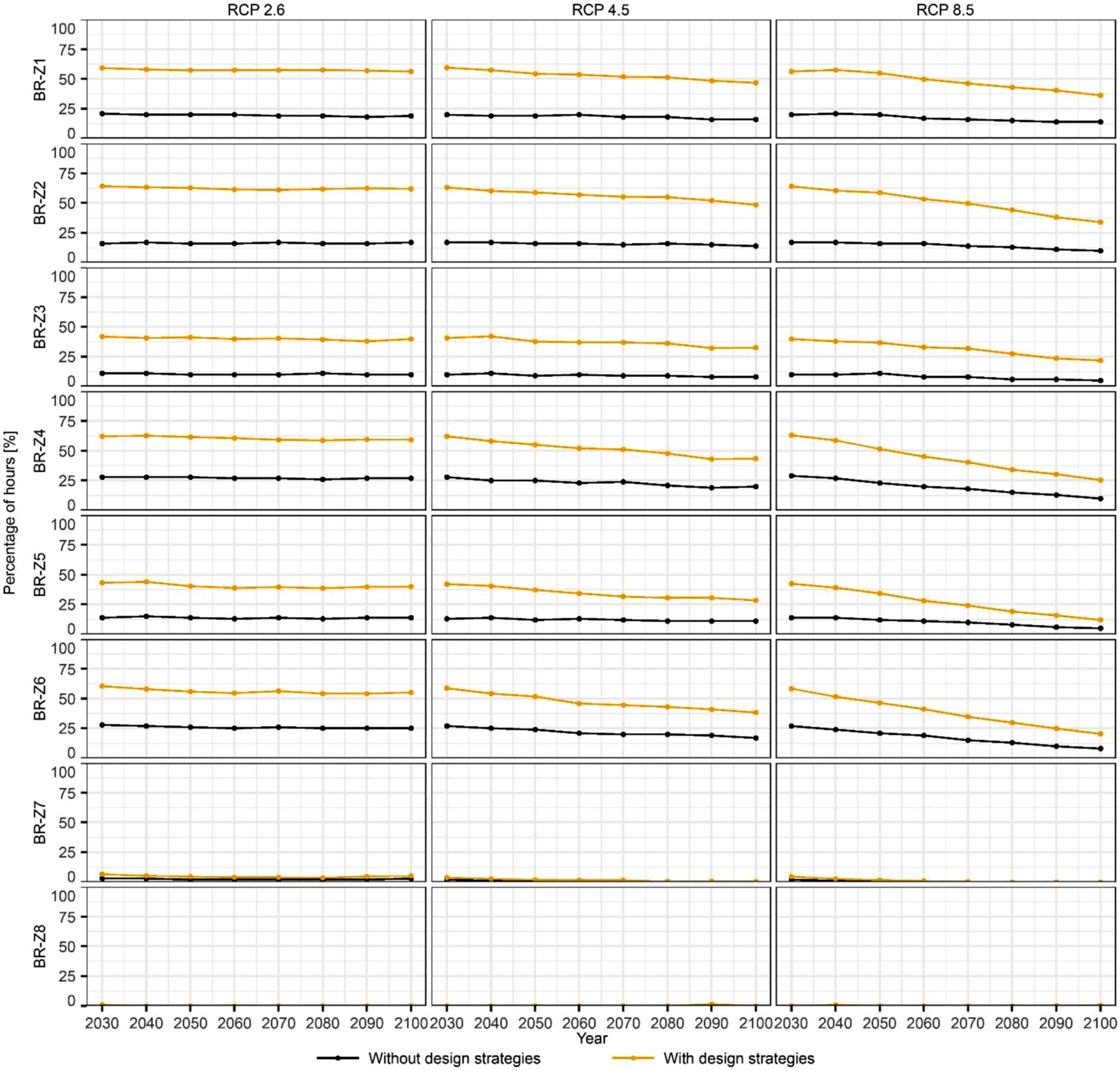


Fig. A2. Evolution of the percentage of thermal comfort hours in Brazil according to both the design of the building and the climate change scenario.

on both the gains of internal loads (DS-8) and the solar gain in high thermal mass elements (DS-10) were the most appropriate in the climate zones in Argentina. These design strategies are like those obtained in Chile. However, the need for using design strategies adapted to cooling in both countries was different. In Argentina, it was appropriate to use design strategies to reduce the cooling load, such as the use of high thermal mass elements with night dissipation (DS-3) or night ventilation (DS-6), with the latter being the most appropriate strategy in all the decades of the 21 st century; in Chile, the percentage of using these strategies was low, and it was obtained only in the combinations of the most severe RCP scenarios at the end of the 21 st century (e.g., RCP 8.5 in 2090 or in 2100). These results followed the same tendency as in Rubio-Bellido, Pulido-Arcas, and Ureta-Gragera (2015) in the cities of Santiago de Chile and Concepción with the A2 climate change scenario. Similarly, the same heating design strategies (DS-8 and DS-10) were more used in Brazil, although the percentage of heating hours were not so high in the climate zones in the country. Likewise, natural ventilation was strongly important in most of the country. The only existing zone in the country where the design strategies were not effective was BR-Z8 because of the high outdoor temperatures. In the European countries considered in the research, the use of heating (DS-8, DS-9, and DS-10) and cooling design strategies (DS-3, DS-5, and DS-6) were appropriate for the various climates in each country. Nonetheless, the effectiveness of the design strategies adapted to heating is expected to be reduced with RCP 8.5.

Thus, these results showed that climate change will vary the effectiveness of passive design strategies in terms of thermal comfort hours. However, the climate zone and the climate change scenario strongly influenced this variation. Thus, achieving international low-carbon goals (RCP 2.6) could guarantee the effectiveness of passive building strategies. However, if other greenhouse gas emissions scenarios emerge, design strategies would be less effective in most of the climate zones due to the double effect produced by the loss of heating energy demand, together with the low effectiveness of passive cooling design strategies due to the increase in outdoor temperatures. Nonetheless, the effects produced by climate change were not negative in all regions. In the cold climate zones analysed in this research, such as the zones in Chile or Argentina, climate change contributed to thermal comfort

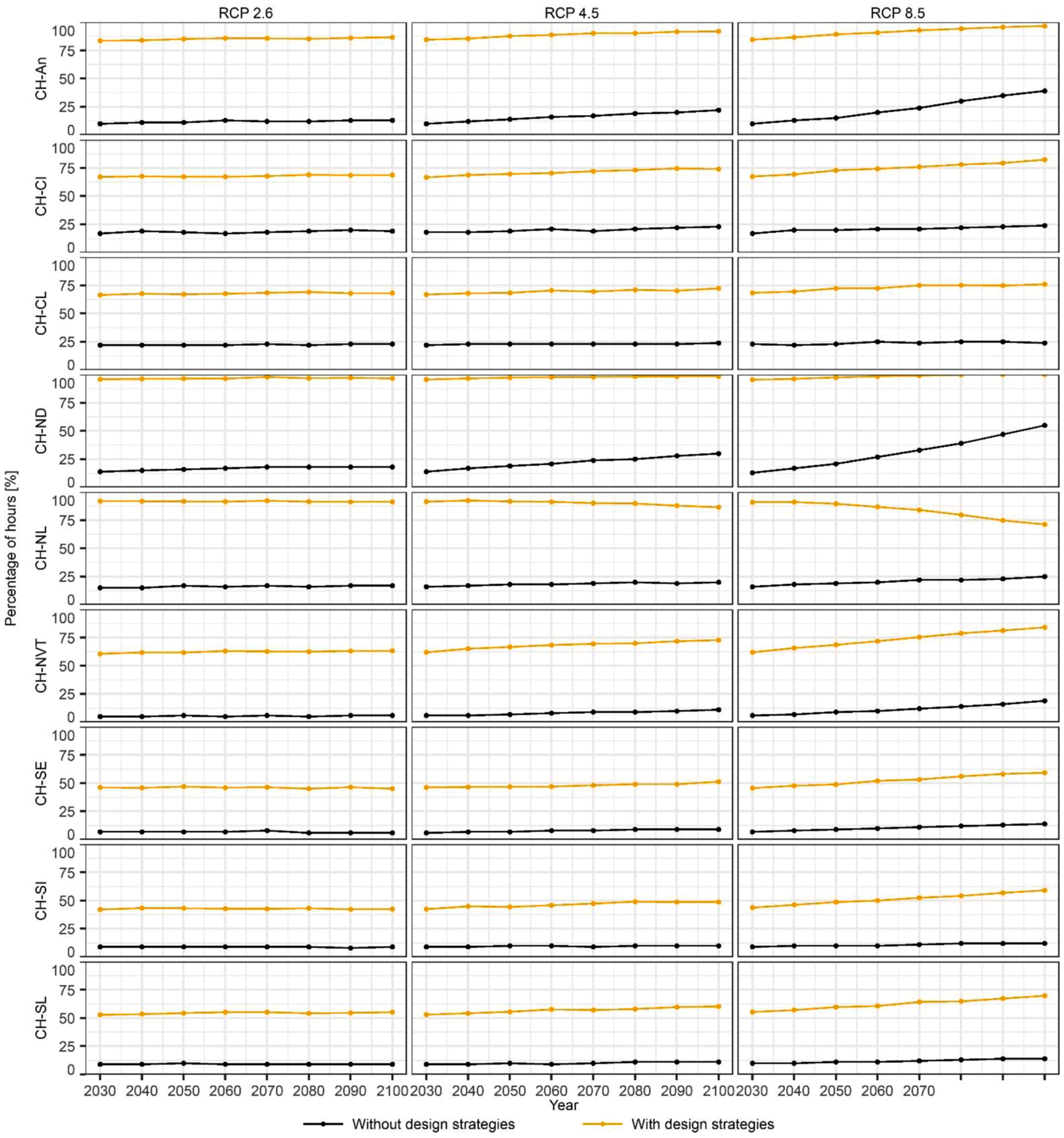


Fig. A3. Evolution of the percentage of thermal comfort hours in Chile according to both the design of the building and the climate change scenario.

conditions and decreased heating energy demand. Nonetheless, this was an isolated aspect as climate change reduced thermal comfort hours in a larger number of zones. Thus, it is imperative to include the use of passive building design strategies with another measure, such as the use of effective HVAC systems (de Rubeis, Falasca, Curci, Paoletti, & Ambrosini, 2020), self-production (Fratean & Dobra, 2018; Lobaccaro, Croce, Vettorato, & Carlucci, 2018; Wu & Skye, 2018) or users' behaviour (Bienvenido-Huertas, Sánchez-García, Rubio-Bellido, & Oliveira, 2020; Huchuk, O'brien, & Sanner, 2020). The decarbonisation goals planned for the building sector would be achieved more quickly by contributing to reach the category of nearly zero energy consumption buildings (Attia et al., 2017). In addition, a better response of the building stock would be guarantee in view of the future climate evolution throughout the 21 st century (Ciancio et al., 2020; Zhai & Helman, 2019)

4. Conclusions

This study analyses the potential of applying passive buildings design strategies in view of the climate change effect. For this purpose, the climate zones in 3 developed countries (France, Portugal, and Spain) and in 3 developing countries (Argentina, Brazil, and Chile) included in the regulations on building energy efficiency were used. In each zone, the climate data of both the current scenario and the RCP scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) were analysed in each decade of the 21 st century. A total of 1,450 climate files were analysed, and the following conclusions were drawn:

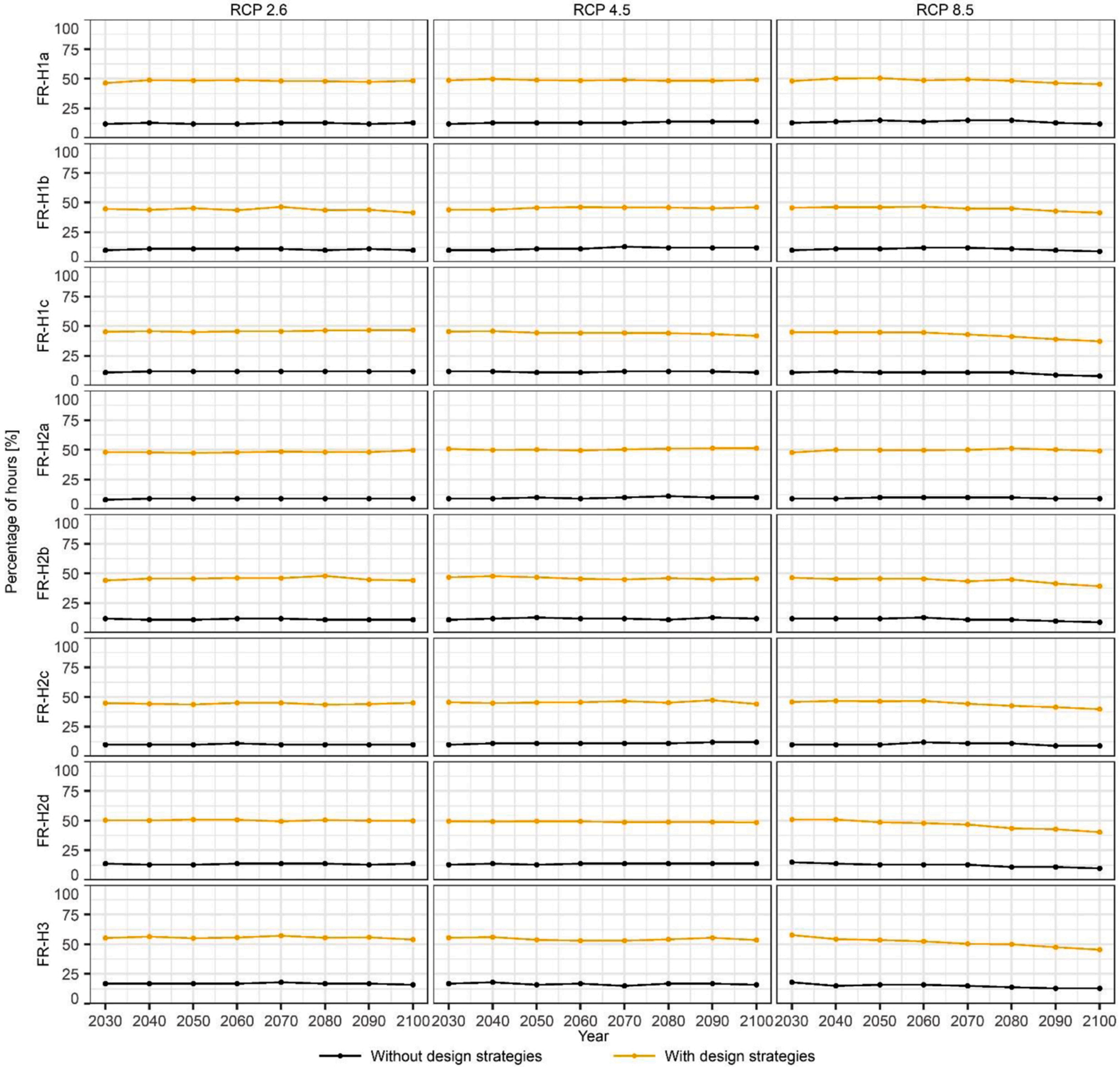


Fig. A4. Evolution of the percentage of thermal comfort hours in France according to both the design of the building and the climate change scenario.

- Thermal comfort in indoor spaces presented various tendencies according to the type of climate and scenario. Thus, RCP 2.6 (i.e., the scenario in which the environmental policies are successful) did not vary thermal comfort hours at the end of the 21 st century. However, RCP 4.5 and 8.5 generated two effects according to the climate: the cold climate zones were favoured by the climate change effect as the number of thermal comfort hours increased, and these hours were reduced in the other zones.
- The use of passive design strategies improved users' thermal comfort in comparison with buildings without these design strategies. In this regard, the buildings with these design strategies obtained an average increase of 41 % in the percentage of thermal comfort hours. Nonetheless, RCP 4.5 and 8.5 could reduce the effectiveness of these strategies to keep a number of thermal comfort hours similar to that of the current scenario.
- The percentage of hours with the need for using HVAC systems was also influenced by the RCP scenarios. RCP 2.6 again obtained almost the same result at the end of the century in comparison with the current scenario, with variations between 1 and 6% in the percentage of hours. However, RCP 4.5 and 8.5 considerably reduced the percentage of heating hours, whereas the percentage of cooling hours increased. This greater prevalence of cooling demand in the future implied an effectiveness loss of the passive design strategies as their capacity is worse to guarantee users' thermal comfort in the hours with a high temperature and humidity.
- Design strategies implied the need for considering dynamic and resilient building designs due to the variability presented by the most appropriate design strategies for each zone according to both the year and the RCP scenario. Thus, the use of dynamic building designs would guarantee a greater adaptation in view of the energy demand variations. In this regard, the use of design strategies based on the gains with internal loads and with high thermal mass elements could be interesting in the short term to reduce the heating demand existing in most zones, although the use of strategies to reduce cooling energy demand (e.g. the use of high thermal mass elements with night dissipation) could be more important in the medium and long term. However, this does mean that these strategies are not used in the current scenario; it depends on the climate characteristics of

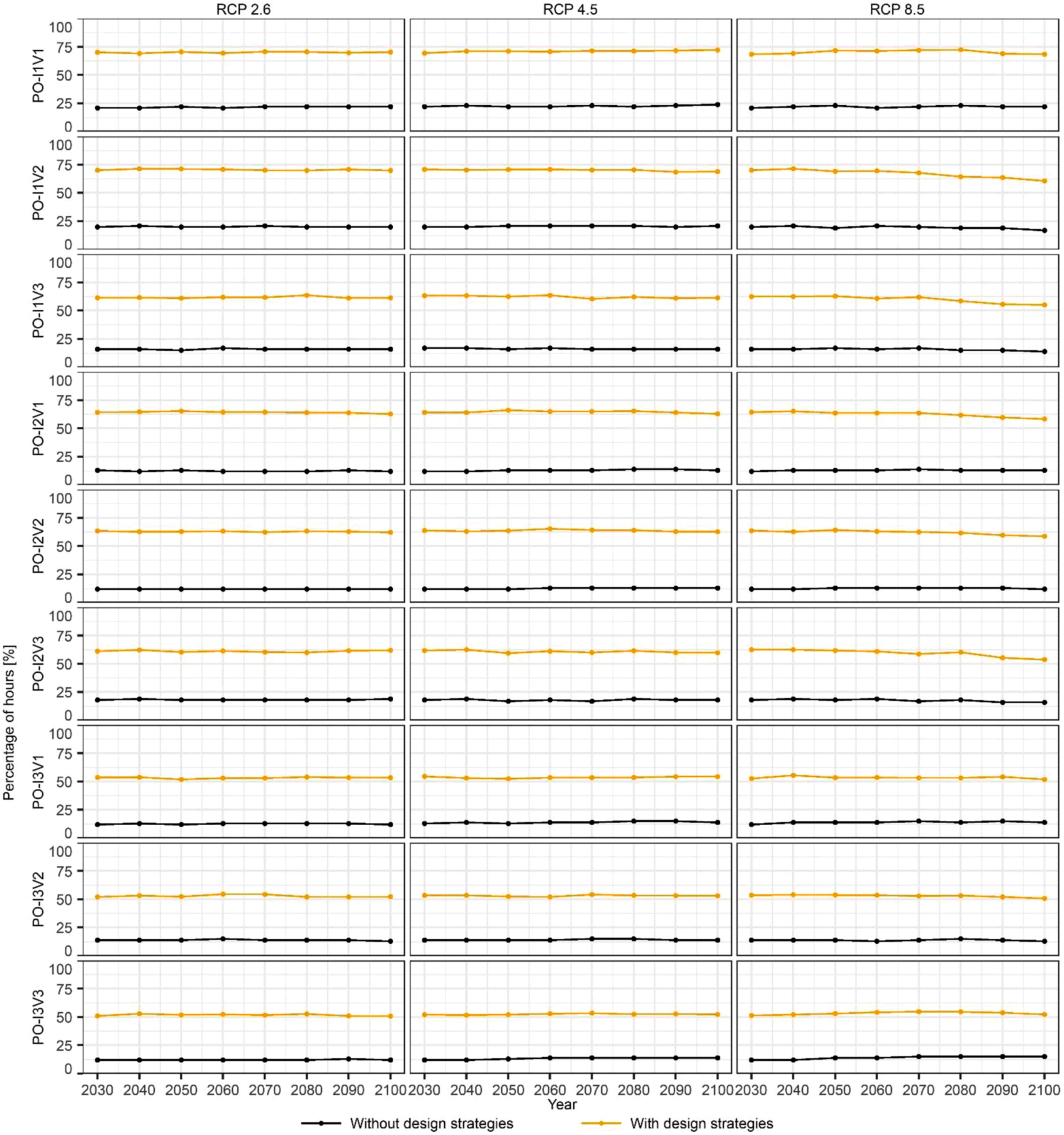


Fig. A5. Evolution of the percentage of thermal comfort hours in Portugal according to both the design of the building and the climate change scenario.

the building. Moreover, the temperature rise estimates could be low in comparison with the actual ones as the effectiveness of the passive strategies could be removed. In this regard, Z8 in Brazil could be an example of how the effectiveness of the strategies could be if a more unfavourable climate than that of RCP 8.5 took place as energy demands could not be reduced with passive strategies.

- The use of data mining algorithms could be helpful to understand the influence of climate change on design strategies and to establish policies. Through the cluster analysis, 5 similarity groups were established between the zones with different centroids. These groups have their own characteristics that differentiate them from the others and allow appropriate design measures to be established; however, the evolution of the climate throughout the 21 st century will vary the similarities among locations. Therefore, both the classification of the zones in the current scenario and the changes expected in the future should be considered. Moreover, multilayer perceptrons are an appropriate tool to estimate the percentage variables of the need for using HVAC systems through the coordinates of the location analysed. Therefore, architects and engineers could use multilayer perceptrons to know the energy requirements of any location without the need for a detailed study.

To conclude, the results of this study are of interest for architects and engineers to have a knowledge framework to design efficient buildings in the regions analysed. Thus, there would be a quicker decarbonisation of the building stock by constructing buildings adapted to the climate and not just as per the current climate but considering the future evolution. Nonetheless, the limitations to guarantee high percentages of

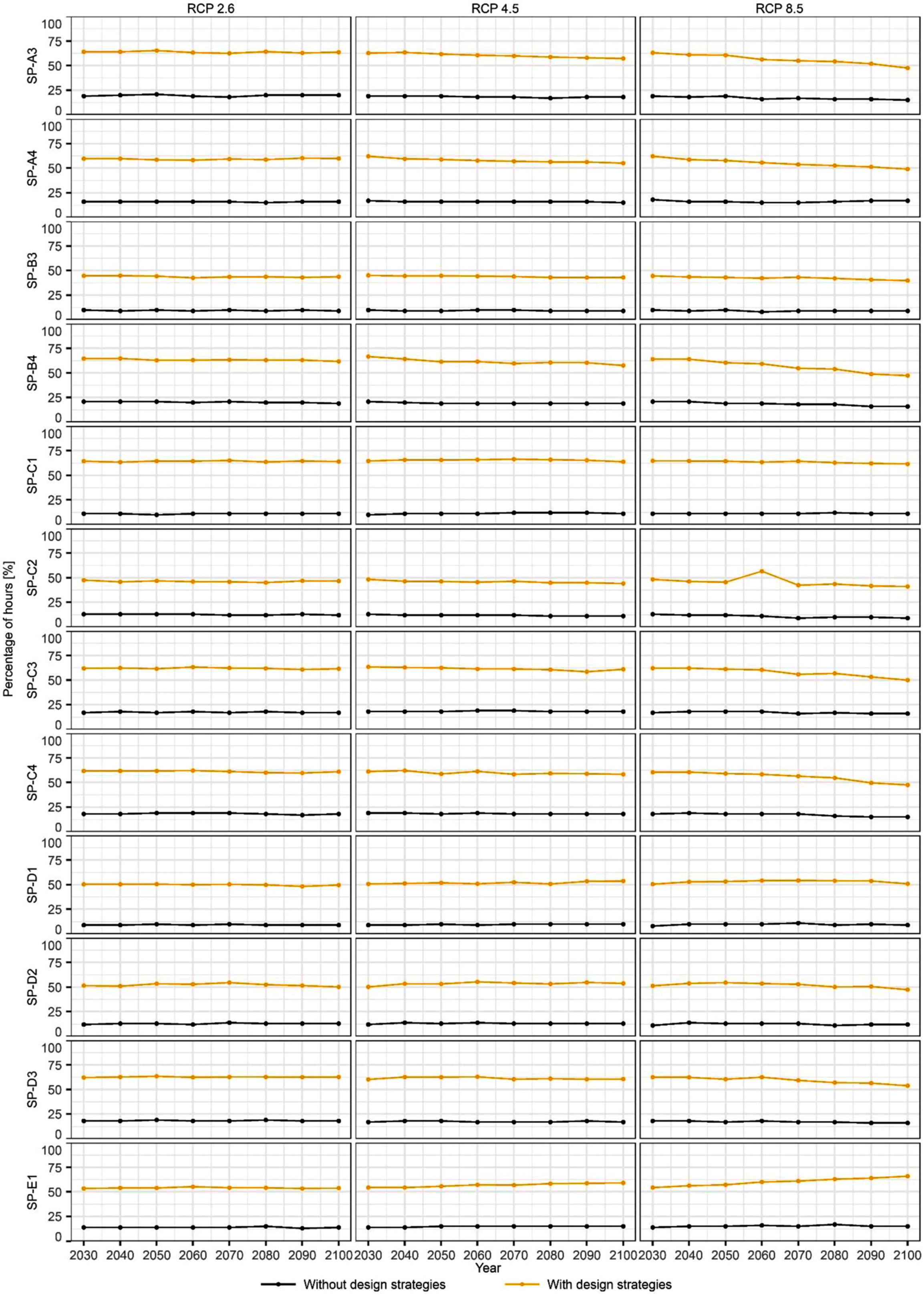


Fig. A6. Evolution of the percentage of thermal comfort hours in Spain according to both the design of the building and the climate change scenario.

thermal comfort hours in the current scenario, together with the effectiveness loss throughout the 21 st century, force to combine passive strategies with other measures, such as effective systems or users' appropriate operational pattern. Moreover, these results are of interest for developing policies and regulations on building energy efficiency. The use of the climate zones included in the regulations of each country guarantees a greater traceability on the part of policy designers to establish effective design criteria. In this regard, this paper shows the progressive effectiveness loss presented by the passive heating design strategies, and passive cooling design strategies could slightly reduce cooling demands. This paper also contributes to understand that standards should be adapted by considering future scenarios because buildings' useful life is long (between 50 and 100 years), so the standards could be energetically out-of-date, thus implying high economic investments. Likewise, the groups obtained with the cluster analyses in the various zones could be a starting point to establish interregional energy efficiency policies and regulations. Thus, these results could facilitate synergies between technicians and politicians from different countries regarding the most appropriate design strategies in each cluster. This is an essential aspect because zones from different countries and continents were grouped together. However, future steps are required to increase knowledge among the various climate zones. In this regard, the results of this study are based on the existing climate analysis in each zone. Future studies should increase the analysis by using specific case studies in each region. For this purpose, the case study should be appropriately selected due to the expected variability in the operational patterns of each country.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

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